NAVAL POSTGRADUATE SCHOOL

Monterey, California

THESIS

A STUDY OF THE EVOLUTION OF THE RELIABILITY AND MAINTAINABILITY ENGINEERING DISCIPLINES

by

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March 1977

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UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER

4. TITLE (and Subtitle)

A Study of the Evolution of the Reliability and Maintainability Engineering Disciplines

5. TYPE OF REPORT & PERIOD COVERED

Master's Thesis
March 1977

6. PERFORMING ORG. REPORT NUMBER

7. AUTHOR(s)

Joseph A. DiPasquale
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8. CONTRACT OR GRANT NUMBER(s)

9. PERFORMING ORGANIZATION NAME AND ADDRESS

Naval Postgraduate School
Monterey, California 93940

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS

11. CONTROLLING OFFICE NAME AND ADDRESS

Naval Postgraduate School
Monterey, California 93940

12. REPORT DATE

March 1977

13. NUMBER OF PAGES

111

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)

Naval Postgraduate School
Monterey, California 93940

15. SECURITY CLASS. (of this report)

Unclassified

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release, distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Reliability - Maintainability

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

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(Page 1) S/N 0102-014-6601 |

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

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A Study of the Evolution of the Reliability and Maintainability Engineering Disciplines

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NOTE:

Reliability and Maintainability have been abbreviated throughout the figures as R and M respectively.

ACKNOWLEDGMENTS

The authors wish to express their gratitude to Mr. Walt Kuzmin, Mr. William Marsh, and Mr. Walt Hardesty of Systems Consultants, Inc. for their assistance in the development stages of this thesis. The authors are also grateful to Mr. Burt Batchelor of Boeing Aerospace and Mr. Clair Cunningham of Ford Corporation for their time and patience in critiquing the taxonomies. Mr. E. J. Nucci of the Electronic Industries Association provided source material that was difficult to find and helped to make our research more complete. In addition, we express our thanks to Mr. Jeff Hall and Mrs. Bernadette Peavy of the Naval Postgraduate School for their assistance in writing and modifying the computer programs, and to Mrs. Mary Roberson of the Naval Postgraduate School for her assistance in Systems Operations. The authors also thank our thesis advisors, Professors Melvin Kline and James Esary for their critique of this thesis, and finally, acknowledgment of the Naval Weapons Center, China Lake for providing the resources required to accomplish this effort.

I. INTRODUCTION

A. BACKGROUND

The ability of a system to be operationally ready when demanded is a function of its design. In the early 1940's, the designer's primary goal was to achieve an output that would satisfy a desired set of specific performance requirements. Major shifts have evolved in this thinking with the rapid advancements in technology since World War II. The emergence of supersonic aircraft, nuclear submarines, moon landers, planetary exploration, laser technology, and complex weapon systems has highlighted the need for efficient and economic designs in terms of system effectiveness and cost. Systems now are required to be both reliable and maintainable in order to be cost-effective over their designed life.

B. PURPOSE OF THESIS

The primary purpose of this thesis is to trace and analyze the evolution of reliability and maintainability as engineering disciplines as evidenced by the published literature. Growth curves are analyzed to determine where the emphasis in reliability and maintainability has been over the past three decades, what the emphasis is today, and, finally, to project probable future discipline emphasis. Secondary objectives were development of a classification structure for each discipline, and development of a

substantial data base of reliability and maintainability documents easily retrieval for research purposes.

C. METHOD OF RESEARCH

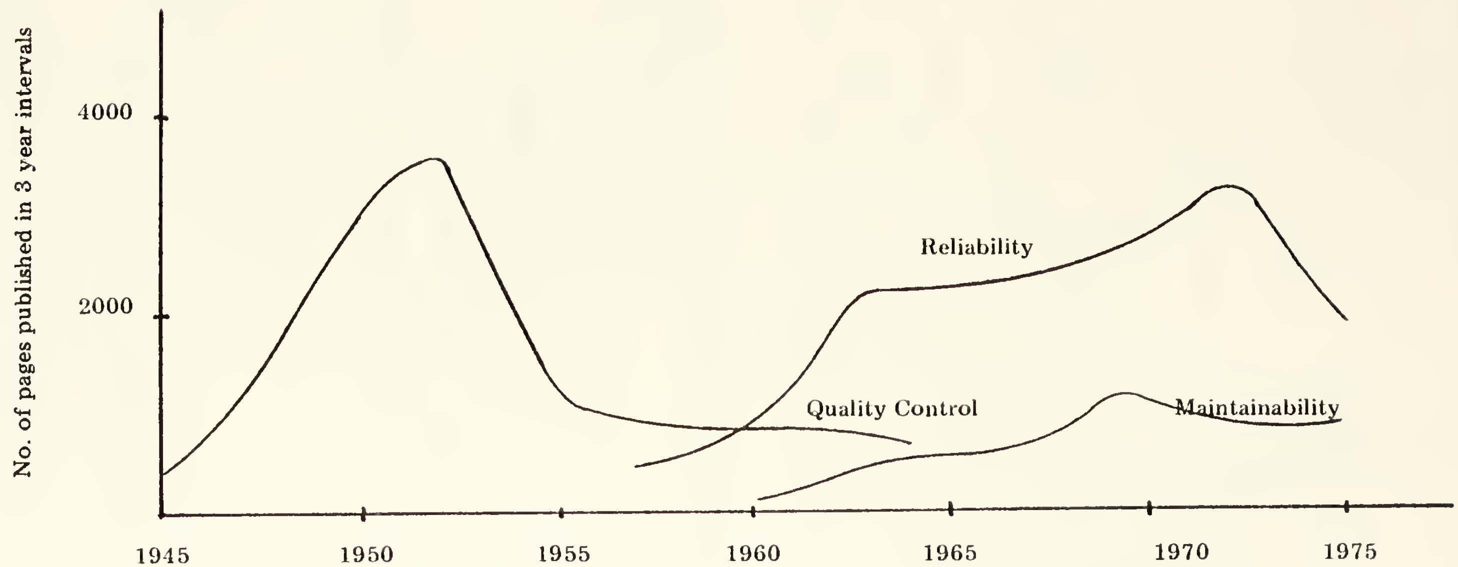
An extensive literature search was performed to develop a factual analysis of the evolution of these engineering disciplines. Several field trips were conducted to interview people who are considered to be highly knowledgeable in reliability and maintainability in order to obtain their perceptions of the evolution of these fields and to solicit their critiques on the proposed classification structures. Such contributions provided valuable assistance in the early phases of the project.

II. EVOLUTION OF RELIABILITY AND MAINTAINABILITY

A. OVERVIEW OF THE EMERGENCE OF RELIABILITY AND MAINTAINABILITY

Literature published on reliability, maintainability, and quality control was researched to identify the emergence of these disciplines and to quantify their growth patterns. Quality control is included because some of the concepts applied in the early reliability writings were developed in the quality control field. The Cumulative Book Index was initially used for this purpose because it is a reasonably complete and comprehensive list of works published in the English language. Also, works listed in this reference must be copyrighted and must have the majority of the material devoted to the subject under which the work is listed. These three factors (English language, copyright, majority of work devoted to listed subject) made the index an ideal source for providing an indication of the growth pattern of the reliability and maintainability disciplines. The Index provided title, author, and number of pages for each work listed. Figure 1 shows the evolution of quality control, reliability, and maintainability as evidenced by books published in these disciplines. The indicator for growth used is the number of pages published in three year intervals beginning in 1944 and extending through 1975. It should be noted here that any conclusions reached using these curves should be treated with care since books have an inherent time lag between original manuscript preparation

Figure 1 Emphasis on R & M from Books



and publication of up to three years. These curves are presented only for the purpose of giving a qualitative feeling for the discipline growths rather than trying to pinpoint exact emergence of the disciplines.

As Figure 1 indicates, books on quality control peaked about 1951 or 1952 and declined thereafter until 1965 when quality control was no longer listed as an entity in the Cumulative Book Index. Reliability began appearing in the early 1950's, and maintainability began appearing in the early 1960's. Research into the periodical literature has provided a more detailed breakout of some of the events which have affected the development of these disciplines.

B. GROWTH OF RELIABILITY AND MAINTAINABILITY BY THE DECADES

1. The Years Before 1940

Reliability principles were used in 1916 by the Western Electric Company which is the manufacturing unit of the Bell System. With production running at a rate of about ten million telephones annually, and rising rapidly, studies were initiated to discover means to produce trouble-free telephone equipment for public use. The Western Electric Company was among the first to realize that the statistical sampling methods already being formulated for science could be applied to industrial processes. The Bell System understood that durability must be a main goal, and that service history and optimization of the design for maximum quality were important factors.

2. 1940 - 1950

The decade began with a national emergency in which there was an urgent need for development of a method for the manufacture of uniform high quality products. The need for greatly increased rates of production lent itself readily to the application of the new statistical techniques. Large quantity production in the rapidly growing electrical and electronic industries led the War Department to develop standards for the application of statistical methods to the quality control of materials and manufactured products. The rapid growth of the electronics industries also brought increasing problems of reliability. Radar and other military developments of World War II introduced the need for specific consideration of reliability.

In 1946, the commercial airlines sponsored field studies of tube and electronic equipment failures. These studies were performed by Aeronautical Radio, Inc., (ARINC).

3. 1950 - 1960

As a result of its work in developing reliable tubes for the airlines, ARINC was requested to make an investigation of military electronic tube reliability. From 1951 to 1954 the program was concerned primarily with the evaluation and improvement of tube reliability. A general report summarizing the findings was published in 1954. The effects of application, environment, and operating and maintenance conditions were shown to be so closely related that the program was redirected to emphasize system reliability as affected by electron tubes. Systems under study expanded to radio

communication systems, radar systems, and bombing and navigation systems.

The recognition by the Department of Defense that many parts other than vacuum tubes were causes for problems led to the formation of the Ad Hoc Group on Reliability of Electronics Equipment (AGREE) in 1952. This group was instrumental in initiating an increasing number of studies in order to add to their knowledge of equipment failures. The AGREE Committee was at least partially responsible for issuance of a Department of Defense Directive entitled "Reliability of Electronics Equipment" which required that additional emphasis be placed on the reliability of electronic equipment.

In 1950, the VITRO Corporation undertook a study of the reliability of Navy shipboard electronic components and equipments. This study resulted in the establishment of the relative failure rates of various parts and in the development of an improved failure reporting system. In the late 50's many other companies made contributions to the improvement of military electronic equipment through field studies carried out under military contracts. These contributions were directed toward the measurement of equipment reliability and the development of methods for predicting the reliability of new electronic equipment while it was still in the design stage.

The recognition of the equipment problems created a sense of reliability awareness during this period. Mass production of systems caused the need for standardized tests

to be used in the factory. Reliability standards had to be developed. Standardization of parts and circuits were stressed. Parts improvement programs were initiated as the quality of parts left much to be desired. Component specifications were now being written. The critical importance of reliability was recognized both in the Department of Defense and in industry. This importance was emphasized with issuance of Military Handbook 217 and Mil-Std-756A for Reliability Predictions as well as Mil-Std-785A for Reliability Program Plans and Mil-Std-781 for Reliability Demonstration Tests.

Prior to 1954, maintainability was not a defined discipline. Some commercial manufacturers were incorporating features later to be known as maintainability features into the design of their products. An example of this was the production of standardized rifles (M1 and Carbine) for the U. S. Army during World War II. The U. S. Army required that the soldier be able to disassemble and assemble each acceptable rifle while blindfolded under combat and inclement weather conditions in mud. An additional requirement specified that the rifle must perform satisfactorily after such as assembly. Therefore, even though maintainability was not yet a widely accepted discipline, the M1 and Carbine rifles demonstrated the feasibility of planning for maintainability in the initial stages of program development.

U. S. Government publications concerning maintainability did not exist in this period. Maintainability requirements were covered through specialized contractual

exhibits and/or amendments to the contracts. By 1959, formalized program specifications started to evolve. The U. S. Air Force maintainability requirements for aerospace systems and equipment (MIL-M-26512) was one of the first.

4. <u>1960 - 1970</u>

This decade witnessed the rapid growth of the maintainability discipline. A realization that the best design from the reliability standpoint may be poor from the standpoint of maintainability created a new challenge for the design engineer. The need for maintainability was predicated on the basis that no system is totally reliable; i.e., the system will eventually fail and therefore considerations must be made on how to return the system to an operational status as rapidly, as effectively, and as efficiently as possible. The awareness of the need to consider reliability and maintainability as design parameters early in system development began to evolve.

The development of integrated circuits and their application during this period increased the complexity and sophistication of hardware. Worst case and statistical circuit analyses were used as design tools. Computerized failure history data banks for use in reliability predictions were developed. Reliability testing using statistically designed tests was introduced and became recognized as a valid test method. The systems effectiveness concept was extensively explored. In 1965 the first Naval Material Support Establishment Systems Performance Effectiveness Conference was held.

MIL-STD-470 was issued in 1966 as the Department of Defense preferred specification for Maintainability Programs. A separate "Maintainability Prediction" Handbook (MIL-HDBK-472) was issued as a companion to the new DOD maintainability standard. With issuance of a standard for maintainability demonstrations (MIL-STD-471) a fairly complete set of maintainability engineering implementation tools now existed.

5. 1970 - 1976

Cost factors became dominant during this period and emphasis was given to considerations such as life cycle cost and design-to-cost. Support costs became manpower intensive, as the average cost of a soldier doubled in these six years. Despite a reduction of defense personnel, operations and maintenance costs rose for fewer operational units, and new systems were being acquired at a slower rate. The extended time in service of the old systems increased reliability and maintainability problems which in turn increased the costs for operation and maintenance.

Reliability methods and procedures developed in earlier periods were refined and were being extended into consumer, energy, and nuclear power areas. The airlines pioneered the MTBF guarantee which requires that the equipment supplier guarantee a stated mean-time-between-failure in the operating environment. If the guarantee is not met the supplier must provide corrective action and provide spares for use. This MTBF guarantee has been modified by the military, and DOD is using Reliability Improvement Warranties as an incentive for contractors to design equipment to meet specified reliability.

In today's atmosphere of increased cost consciousness, there is continued emphasis on reliability and added emphasis on maintainability. The defense community emphasizes the total cost of ownership, the largest component of which is operating and support costs. This is leading to a search for innovative approaches to improve equipment maintainability.

III. METHODOLOGY

A. INTRODUCTION

It is apparent that reliability and maintainability have evolved from rudimentary concepts into full scale scientific disciplines over the past thirty years. To analyze this evolution, it was necessary to devise a means to measure their evolution and identify data sources applicable to the measurement technique. This chapter addresses the measurement technique, data sources, and validation procedures utilized.

B. METHOD OF MEASUREMENT OF DISCIPLINE DEVELOPMENT

It was desirable to employ a measure that would give as accurate a representation as possible across the full spectrum of both disciplines. Dimensions which were considered in the selection of a measurement method included the impact of reliability and maintainability on industrial products both from user and producer viewpoints, growth measurement of such areas within the disciplines, applications, and available data base. It was considered important that the growth measure selected be broad enough to span all of the above considerations without a significant risk of data skewing.

Several measures of discipline development were considered and the measure ultimately chosen was the number of articles published in the open literature because this

measure provided the broadest coverage of the disciplines with the least amount of bias. Other measures, such as government specifications would tend to place undue emphasis on weapons systems and/or space related systems as opposed to consumer capital items or construction equipment. Focusing on commercial, industrial related measures would have de-emphasized reliability and maintainability impacts derived from the rapid state of the art advances in technology resulting from defense and space activities. Industries (particularly commercial products) tend to make small incremental changes in their product technology levels whereas DOD and NASA tend to make quantum jumps. In one way or another all of the alternatives bias the data. However, it appeared that tracking the open literature, such as annual reliability and maintainability symposia, on a yearly basis would provide the broadest indicator of discipline development.

1. Discipline Structure Development

Once the method for measuring discipline development had been selected, it was necessary to address questions concerning the breakdown of each discipline into subelements. Initially it was unclear how to subdivide them and to what depth. The disciplines could, for example, be divided into functional and application oriented subelements or they could be subdivided by the physical and mathematical sciences forming the core of underlying theory. All of these subdivision alternatives had merit, and it was decided to incorporate them into a hierarchical classification system. As a result, a taxonomy was developed whereby articles could

be classified and the data stored for future analysis as well as providing a mechanism for article retrieval for research purposes. The taxonomy provided an excellent structure for analyzing the development of these disciplines along the dimensions mentioned earlier. It was particularly useful in defining the main branches and emerging subbranches of the scientific core of the disciplines.

The keywords were initially selected by researching a representative sample of the available literature and through successive refinements were finally arranged into a classification structure. The final determination of keyword location in the taxonomy and the phrasing of keyword definitions was not a trivial effort. Consider, for example, whether prediction should merit its own elemental category, be included with statistics as a subelement under quantitative methods, or be included as a subelement under analysis. At one time or another in the development of the taxonomy, prediction was classified as all three. Eventually, it was agreed that prediction was most frequently utilized in practice as an analysis technique and it was positioned in the taxonomy accordingly. Similar iterations have been performed on most of the main branches of each discipline in arriving at the final structural relationships.

The structure was then presented to several persons with extensive experience in the fields of reliability and maintainability for comments. This process was iterated several times and resulted in the taxonomies presented in Figure 2 (Reliability) and Figure 3 (Maintainability).

2. Keyword Definition Consistency

Along with the determination of an appropriate classification structure, it was particularly important to maintain consistency in the manner in which articles were classified in the structure. For consistency, it was necessary for everyone involved in the study to have a clear understanding of keyword definitions within the context of discipline usage. There did not appear to be a universally accepted glossary of reliability and maintainability terms available from the literature. Where possible, generally accepted definitions were used. However, in some cases it was necessary to develop definitions either because none existed or because there were conflicting usages in the literature. Considerable effort was expended early in the study to converge on a set of keyword definitions and to solicit comments on the proposed definitions from experienced leaders in their respective disciplines. The definitions finally arrived at are included in Appendix A.

Each article classified was studied to determine the author's intended thrust and appropriate keywords were chosen to describe the primary thrust at each level in the hierarchy. If secondary objectives were identified, these also were classified. However, it was considered important to determine the primary thrust first as this would insure that the articles were read in sufficient depth to minimize classification errors. The main keyword classification system presently in use in the literature has evolved from the ASQC system over a period of years without a great deal of planning either

with regard to future expansion or consistency with past evolution. It was also apparent that authors had classified their own works, and in many cases this led (in our opinion) to a substantial portion of the articles being classified with inappropriate keywords.

Attempts were made to use the keywords already assigned to certain articles but this proved difficult and even misleading. In a few cases it was apparent that the author had attempted to expand the scope of his article by inappropriately expanding the keyword designators. It was felt that the lack of generally accepted keyword definitions combined with the need for a clearly defined and documented structural relationship of the keywords within the disciplines greatly contributed to the article author's classification problems. Recognition of this situation and desire for measurement consistency contributed to the taxonomies depicted in Figure 2 and Figure 3.

C. TAXONOMY CONSTRUCTION

The taxonomies are arranged in a hierarchical order for the two engineering disciplines. The top three levels, functions, applications (general), and applications (specific) were established to enable discipline growth to be measured along these dimensions as well as within the branches or elements of the discipline. In terms of growth measurement, it appeared worthwhile to provide a means for separating government-oriented applications such as defense and space systems from industrial

FIGURE 2 RELIABILITY TAXONOMY

FUNCTIONAL AREA

- Electrical
- Electronic
- Electro-Mechanical
- Hydraulic/Pneumatic
- Optical
- Chemical
- Non-Reversible
- General

APPLICATION (GENERAL)

- Consumables
- Consumer Capital Item
- Industrial Short Life or Low Cost
- Industrial Long Life or High Cost
- Service
- Construction
- AEC/ERDA
- NASA
- DOD
- Government, Other
- Unspecified

APPLICATION (SPECIFIC)

- Ground Air Space Transportation
- Ocean
- Communications
- Medical
- Computational (Hardware/Software)
- Power Generation

BRANCH

- Management
  - Reliability Program Management
    - Organization & Management
    - Evaluation & Assessment
      - Case Studies Studies
      - Program Evaluation
      - Design Review
    - Data Exchange
    - Education & Training
    - Field Activity
  - Cost
    - System Effectiveness
  - Failure Recurrence Control
  - Procurement
    - Specifications
    - Contracts
    - Warranties
  - Product Liability
- Design
  - Component Related
    - Part/ Material Selection
    - Component Testing
    - Redundancy
    - High Reliability Parts
  - Engineering Analysis
    - Criteria/ Requirements
    - Tolerance/ Safety Factors
    - Human Engineering
    - Test Equipment
    - Burn-in
- Analysis
  - Configuration
    - Modeling/ Simulation
    - Failure Analysis
    - Fault Tree
    - FMEA
    - Block Diagrams
    - Design Reviews
    - Criticality Analysis
  - Prediction
    - Parameter Prediction
    - Probability Distribution
    - Apportionment
  - Reliability Growth
- Data
  - Processing/ Utilization
  - Collection
- Theory
  - Theory of Failure
  - Renewal
- Test & Evaluation
  - Methods
  - Statistics
    - Bayesian
    - Parameter Estimation
    - Sampling Plans
    - Design of Experiments
    - Confidence Level
    - Goodness of Fit
  - Reporting/ Evaluation

FIGURE 3 MAINTAINABILITY TAXONOMY

- FUNCTIONAL AREA
  - Electrical
  - Electronics
  - Electro-Mechanical
  - Hydraulic/Pneumatic
  - Optical
  - Chemical
  - Non-Reversible
  - General
- APPLICATION (GENERAL)
  - Consumables
  - Consumer Capital Item
  - Industrial Short Life or Low Cost
  - Industrial Long Life or High Cost
  - Service
  - Construction
  - AEC/ERDA
  - NASA
  - DOD
  - Government, Other
  - Unspecified
- APPLICATION (SPECIFIC)
  - Ground Air Space Transportation
  - Ocean
  - Communications
  - Medical
  - Computational (Hardware/Software)
  - Power Generation Generation
- BRANCH
  - Management
    - Organization & Management
      - Planning & Implementation
      - Evaluation & Assessment
    - Logistics
    - Availability
    - Availability
    - Costs
      - Systems Effectiveness
    - Procurement
      - Contracts Specifications
  - Theory
    - Measures
    - Modeling
  - Design
    - Qualitative Attributes
    - Quantitative Attributes
    - Maintenance Concepts
    - Human Engineering
    - Trade-offs
    - Test Capability
    - Safety Factors
  - Analysis
    - MEA
    - Modeling/Simulation
    - Design Reviews
    - Prediction
  - Data
    - Collection
    - Reduction & Processing
    - Utilization
    - Design Disclosure Formats
  - Test & Evaluation
    - Testing/Demonstration
    - Reporting
    - Analysis/Evaluation
    - Statistics

applications such as process control. As shown in Chapter IV, it is interesting to correlate various functional activity levels with elemental or branch developments. An example of this might be correlation of Department of Defense influence on analysis of reliability in electronics systems. The levels of ultimate interest, of course, are the elements and subelemental development trends in both disciplines. Tracing of the development of these lower levels chronologically provides a great deal of insight into how the disciplines evolved to their present status, and correlation with the upper levels provides an insight into the underlying factors influencing their development. A secondary objective can be realized by retaining these upper levels because they greatly aid in document identification and retrieval for research purposes.

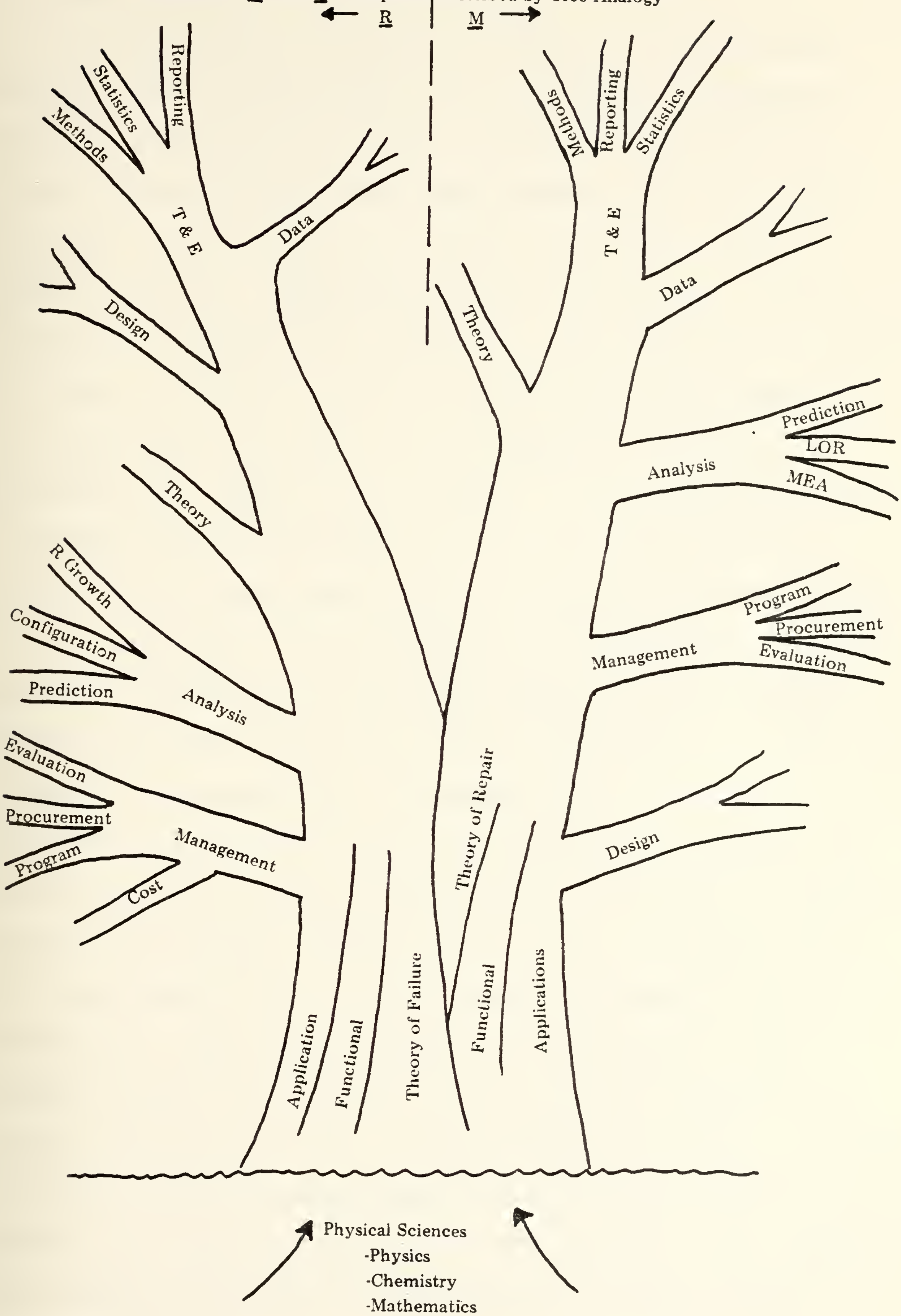
As indicated in Figure 2 and Figure 3, the keyword structures for reliability and maintainability have a great deal of similarity particularly at the upper levels. This is not accidental nor is it inappropriate if one considers that the disciplines are heavily interdependent in terms of both application and functional dimensions. Emphasis and hence growth stimulus have varied greatly within the functional categories over the years. For example, government agencies such as the National Aeronautical and Space Administration (NASA) have been extremely interested in reliability whereas the Department of Defense (DOD) has emphasized both reliability and maintainability in a more balanced sense.

In attempting to visualize the development of these disciplines, it is helpful to compare their development to that of a tree as pictorially illustrated in Figure 4. One might represent the roots (which supply nutrients for growth) as the sciences of mathematics, chemistry, physics. These supply the technology and innovation for discipline development. The trunk represents the core of the disciplines such as theory of failure and theory of repair. The branches represent growth of elements and subelements. As the tree grows certain branches exhibit high growth rates and then tend to stabilize or even stagnate and die. These same characteristics are exhibited in both the reliability and maintainability discipline developments. Thus, the analogy is helpful in visualizing the growth patterns.

In drawing this analogy it is noted that maintainability has developed along similar lines to reliability and in many ways, was an outgrowth of reliability. It should be noted that basic differences between the two disciplines are primarily due to different underlying concepts and theory.

In the analysis which follows in Chapter IV, reliability and maintainability are treated as separate entities, and growth of branches and subbranches within each discipline is measured and analyzed. The similarities and differences referred to in the preceding discussion become more apparent as the measurement and analysis of their development from a chronological standpoint is discussed in detail.

Figure 4 R and M Disciplines Described by Tree Analogy



D. DATA SOURCES

In attempting to quantify the growth of the various branches within disciplines, it was decided to emphasize articles published in the open literature as opposed to books because articles were much narrower and more specific in scope. Books tend to be tutorial in nature, and in general, are not representative of the taxonomy. It was necessary to examine and classify a large number of articles in order to develop a data base which was large enough to be significant and which, in the aggregate, would have minimum bias. There is, of course, a much larger data base available and the challenge was to select those sources which would be most suitable for the purposes of this thesis. It was desirable to include articles from sources which were somewhat continuous in nature and which, in the aggregate, covered the broad spectrum of both disciplines. It was important to ensure that a concentration of articles covering a narrow spectrum of the disciplines were not incorporated in any given time interval. Otherwise, conclusions based on the sample results would not be representative of the total population. In this regard, reliability and maintainability symposia proceedings were selected as the primary sources for articles since they are continuous in nature and tend to cover a broad spectrum of topics. Several different symposia were chosen since each one tends to emphasize different branches of the disciplines, and together they appear to provide a well-rounded coverage of each discipline.

Time phasing of these sources and their respective mergers, terminations, etc., is shown in Figure 5. For reasons of simplicity, as symposia and proceeding titles changed frequently, the most recent symposia proceedings titles were used. A complete list of article sources chosen for analysis of discipline growth is presented in the List of References. The reference numbers in the figure correspond to the identifier numbers in the List of References. As indicated by Figure 5, the sources selected span the time period of interest with reasonable consistency and, in aggregate, represent approximately 4,000 articles. Two seemingly reasonable sources were not included in the data base. The Proceedings of the West Coast Reliability Symposium were not available. The Reliability Abstracts and Technical Reviews published by NASA between 1960 and 1970, did not appear to have reliability as a major thrust (abstracts of various reliability symposia excepted). In addition, they were of such brevity to make classification to the desired depth extremely difficult, thus greatly increasing the risk of erroneous classification.

Figure 6 indicates the relative contribution each of the sources made to the overall data base used for intra-discipline growth analysis. The data base for reliability was reasonably continuous and uniform in density. The data base for maintainability, however, was very spotty with conferences lasting only a few years before termination. Maintainability is hard to find in the open literature after 1970.

Figure 5 Literature Sources

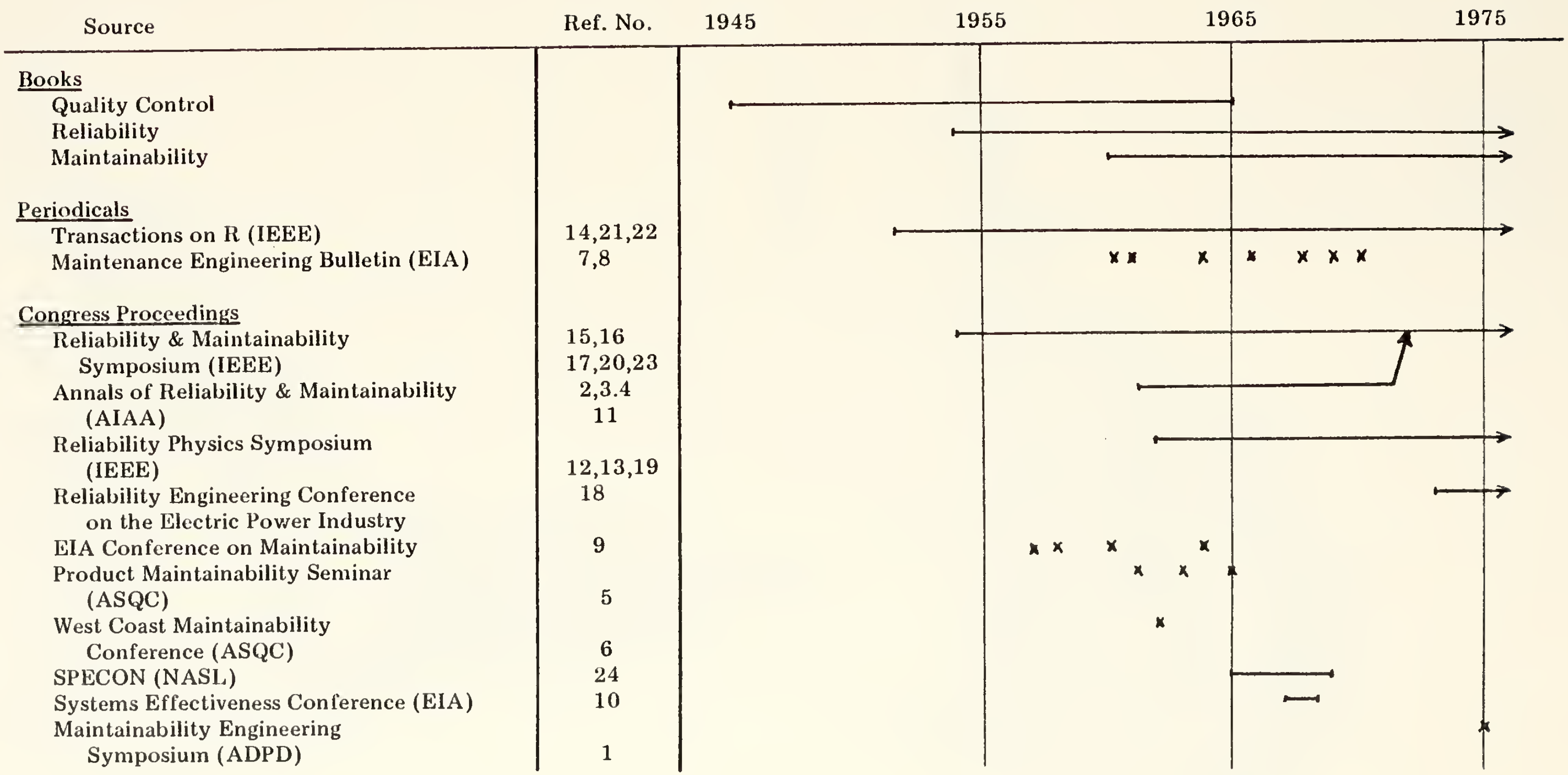
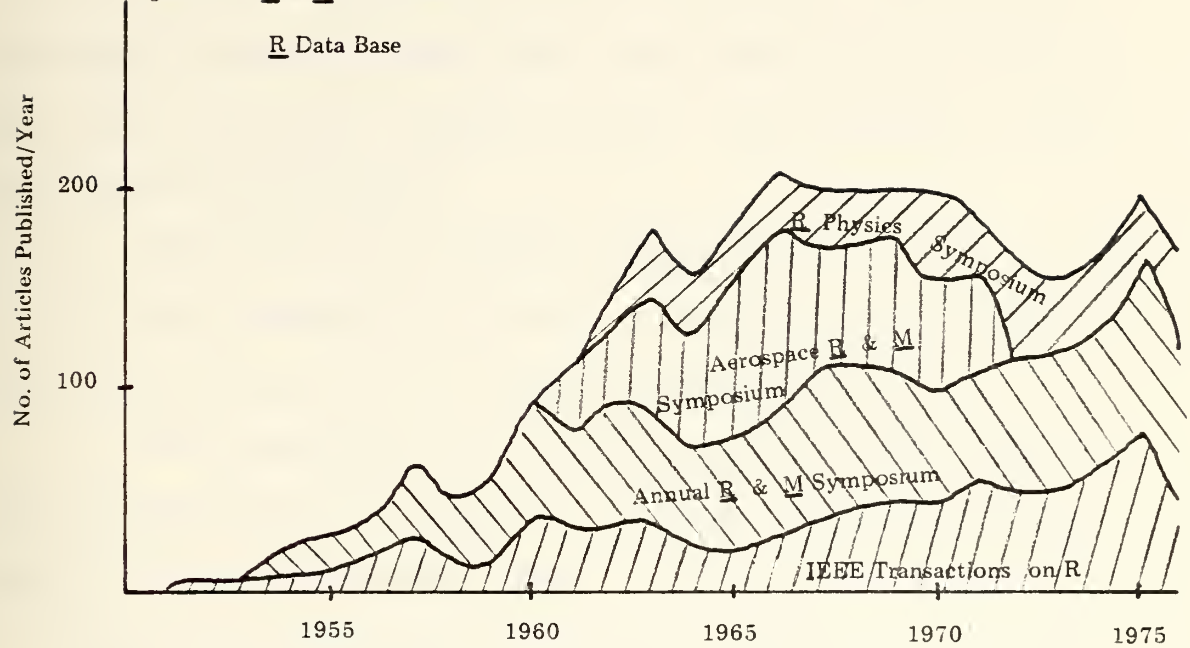
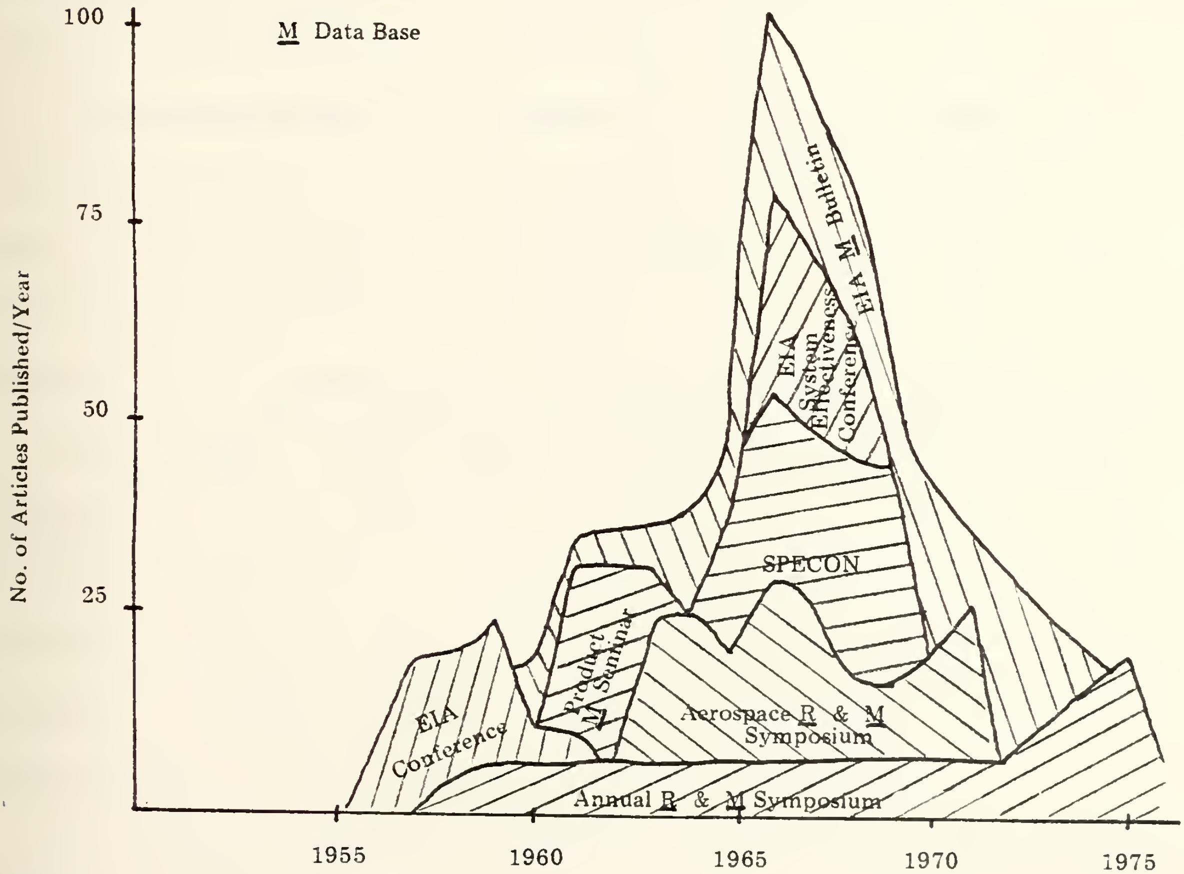


Figure 6 R & M Data Bases





It was decided that the Proceedings of the Annual Reliability and Maintainability Symposium would be an excellent base for developing the taxonomy. These proceedings started in 1954, and, with the exception of 1955, have been published annually since. The reasons for this decision were multiple:

1. The source was readily available.

2. The proceedings present a continuous and long time span of articles in the reliability discipline.

3. The proceedings are a representative and comprehensive collection of articles encompassing the range of skills within the disciplines.

From initial readings of the proceedings, it became apparent that the taxonomy for reliability could readily be constructed from the article content.

The taxonomy for maintainability, however, could not be constructed from this source because of an insufficient quantity of articles. The proceedings were not officially designated a maintainability source until 1972 when the title changed from Proceedings of the Annual Symposium on Reliability to Proceedings of the Annual Reliability and Maintainability Symposium. This occurred as a result of the merger of the Aerospace Reliability and Maintainability Symposium with the Annual Symposium on Reliability as indicated by the arrow in Figure 5. Other sources, therefore, were investigated for development of the taxonomy for maintainability.

The Maintainability Committee of the Electronics Industries Association (EIA) compiled two volumes of a maintainability

bibliography, with the first covering the period to 1964 and the second covering the period 1964-1968. These two volumes represent the first decade of active development of the maintainability discipline. A close scrutiny of this reference was made in an attempt to locate a source or sources that would offer the same advantages for research as the <u>Annual Reliability and Maintainability Symposium Proceedings</u>. An initial source selected was the <u>Proceedings of the NMSE Systems Performance Effectiveness Conference (SPECON)</u> which was in existence from 1965 to 1969. This source was primarily concerned with qualitative aspects and was deficient with regard to the quantitative aspects of maintainability. A second source was selected, <u>Proceedings of the EIA Conference on Maintainability of Electronic Equipment</u>, which covered the years 1957 to 1963. Now, with the <u>Annual Reliability and Maintainability Symposium Proceedings</u>, an overview of Maintainability existed for the period 1957 to 1976. It is from these sources that the taxonomy for Maintainability was established.

E. TAXONOMY VALIDATION

Throughout the development of the taxonomy, the classification scheme was subjected to a series of checks, primarily relating to the naturalness of the keyword groupings and their relation to the scientific basis for the underlying theory. The initial groupings were taken from the American Society of Quality Control (ASOC) classification system and were subsequently refined and modified as more insight was gained through research of the literature. As the taxonomies

evolved, many ambiguities and inconsistencies surfaced which required resolution. This was accomplished by conversations with experienced practitioners in the fields of reliability and maintainability and by a trial run consisting of classifying a large number of articles to expose the broad spectrum of subbranches within the disciplines. As experience and depth of knowledge about the disciplines increased through exposure to the literature, it became progressively easier to resolve the ambiguities.

In a less formal, yet equally meaningful sense, the taxonomy was validated when articles began to be classified with relative ease. Finally, a classification scheme was developed that corresponded to the opinions of the practitioners and which appeared to fit the patterns established by an analysis of the literature content.

F. DATA STORAGE AND RETRIEVAL

It was apparent from the beginning of the thesis research that, because of the large number of articles to be read and classified, there would be a monumental task associated with the storage, control, and manipulation of the data. To maintain control, each article was assigned a series of codes which served to distinguish it from all others. An IBM 360/67 computer was used to store and manipulate the generated data. This allowed for data storage by article title, author, date of publication, publisher, keyword, and combinations thereof. Specific information regarding the assignment of keyword codes, data update procedures and

related computer programs is included in a User's Manual written as a companion document to the thesis.[1] Each article entered into the data bank was analyzed for content, and classified by keyword according to the taxonomy developed and presented earlier. This data (number of articles by keywords) was then recalled, totaled by year for each keyword, and plotted in the form of a histogram. The histograms provided considerable insight into significant changes in emphasis which occurred in the time period of interest. The data was then summed and plotted in a cumulative form to gain a perspective of the overall growth characteristics of each branch. This also provided a good indication of branches which had matured or which were in the process of maturing.

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[1]Masten, R. L., Hamilton, T. A., and DiPasquale, J. A., User's Manual for "A Study of the Evolution of the Reliability and Maintainability Engineering Disciplines" Computer Programs, Naval Postgraduate School, 1977.

IV. ANALYSIS OF RELIABILITY AND MAINTAINABILITY DISCIPLINE EVOLUTION

A. INTRODUCTION

This chapter addresses the evolution of the reliability and maintainability disciplines from a chronological standpoint. The measurement technique discussed in Chapter III is used to analyze the development of the disciplines along the branches and subbranches depicted in the taxonomies. Each discipline is analyzed as a separate entity in terms of its internal development. Similarities and differences in the development of the two disciplines are noted in the concluding section of this chapter.

B. RELIABILITY DISCIPLINE GROWTH

The overall trend of the reliability discipline is discussed before analyzing its intradisciplinary growth. Figure 1 presented in Chapter II provides one measure of the overall discipline growth using number of pages published in book form as the measure of growth. Books, however, do not present the whole picture because of the time lags associated with publishing large works and because of the wealth of literature published in short article form. To gain a perspective of the overall discipline growth a composite picture was formed using both books and short articles. Figure 7 presents this composite overview, and again the unit of measure is number of pages published in a three year interval. This unit of measure is necessary in

Figure 7 R Discipline Emphasis

order to directly compare books and articles, and it also provides a smoothing function so that the long term trend is discernible.

Figure 7 indicates that interest in reliability gradually increased from the early 1950's to about 1960 and then dramatically increased until about 1970. After 1970 there appears to be a gradual decline in growth. Reasons underlying this phenomenon can only be conjectured at this point. The growth during the 1960's can be largely attributed to the intense interest of the National Aeronautics and Space Agency (NASA) and the Department of Defense (DOD) and the accompanying financial resources which stimulated the aerospace industry in this time period. The decline noted during the early 1970's could be the sign of a maturing discipline, or it could be due to economic factors, since both space and defense have suffered budget cut-backs (especially in research and development) in this time frame. The decline is probably a combination of the above factors. However, the economic constraints are likely to be predominant because technological advances which allow development of increasingly complex systems stimulate technical innovation from reliability engineers.

C. RELIABILITY INTRADISCIPLINE GROWTH

The method of analysis utilized to determine the growth characteristics of the branches and subbranches of each discipline has been discussed in Chapter III. For the periodical literature, the measurement indicator is number

of articles published per year, and is plotted in the form of cumulative histograms for each of the branches and twigs identified by keywords. The branch, subbranch, and twig (using the tree analogy) growth patterns will be investigated prior to correlating these elements with the upper divisions in the taxonomy.

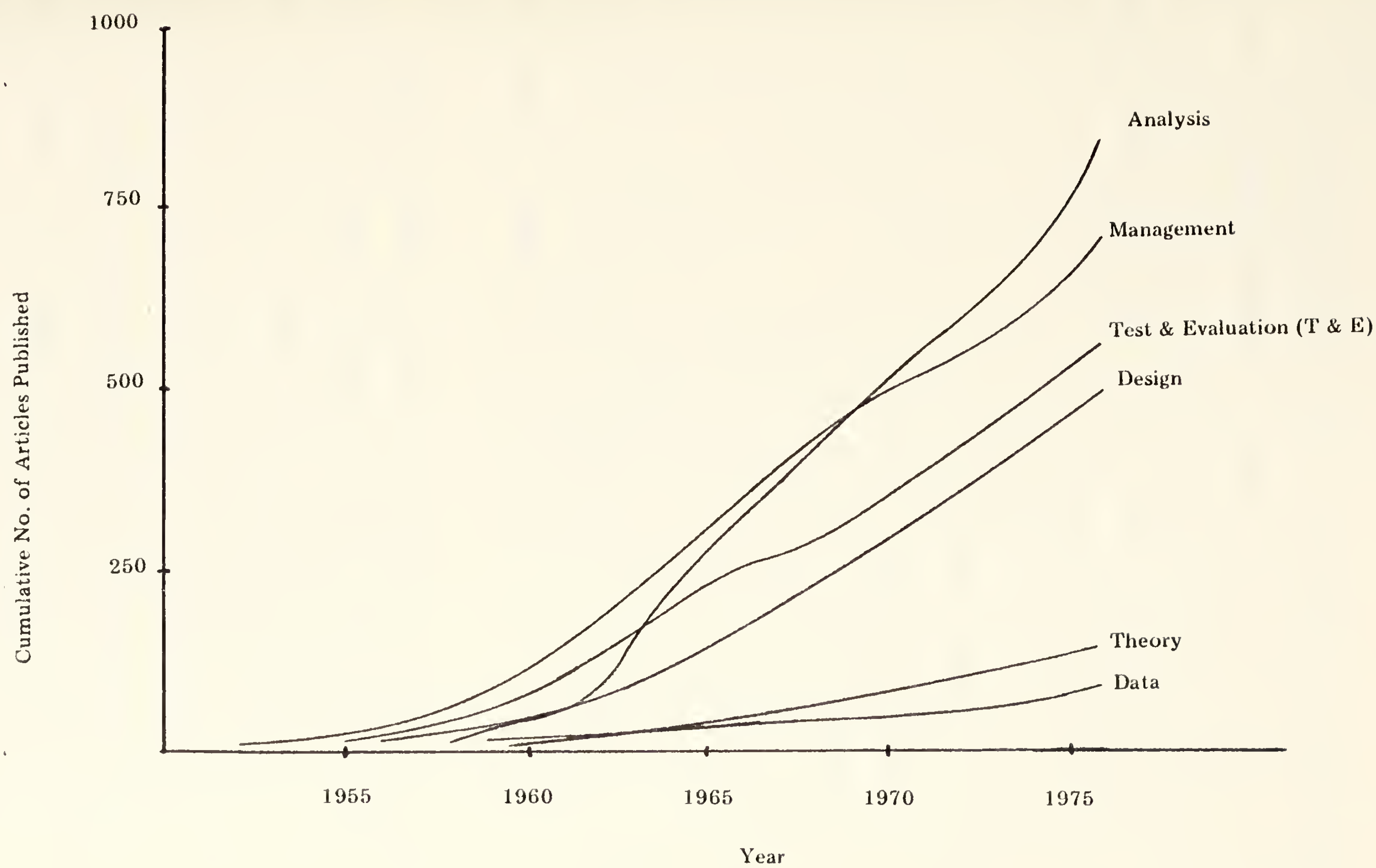
1. Reliability Branch Growth Trends

Analysis of the main branches of the taxonomy (theory, design, etc.) was performed utilizing the cumulative number of articles published during the time interval of interest. This is a measure of the interest and resources which have been applied to the various branches of the discipline over the past twenty-five years, and represents the accumulation of knowledge within each branch. This data is graphically presented in Figure 8 for the period from 1950 to 1976.

The amplitudes of the curves provide a good indication of the relative attention paid to the various branches. The curves indicate that management, analysis, test and evaluation, and design received far more emphasis than did theory and data. The slope of the curves indicates the emphasis that each branch received at a particular instant in time.

Theory and data (which includes systems and techniques for collection, processing and utilization of the data) appear to have small and reasonably constant growth except for a slight increase in emphasis in 1975 and 1976. The other four branches indicate a substantial increase in

Figure 8 R Branches



emphasis in the 1960's and 1970's. Analysis exhibited the most dramatic change, primarily due to the influence of NASA and DOD.

The starting points for the various curves show when the literature began to emphasize each branch, and do not imply that there was nothing written previously. Management emerged early in the late 1940's and early 1950's, providing the transition from the quality control era into the reliability era. This phenomenon was also noted in books as those works slowly transitioned from emphasis on quantitive aspects such as statistical sampling theory to qualitive aspects of process control, and management structures for quality control. Theory apparently emerged (late 1950's) shortly after design and analysis. This seems reasonable, since in the process of design for fewer failures, and in the analysis of failures, engineers and scientists probed deeper into the underlying physical causes of failure in devices.

These curves provide an overview of the growth patterns of the main branches of the discipline and it appears that none of them have reached maturity. Analysis and Management show strong tendencies toward increased emphasis in the immediate future. Within each main branch there are several subbranches which also have pronounced growth patterns and these are discussed in the following sections.

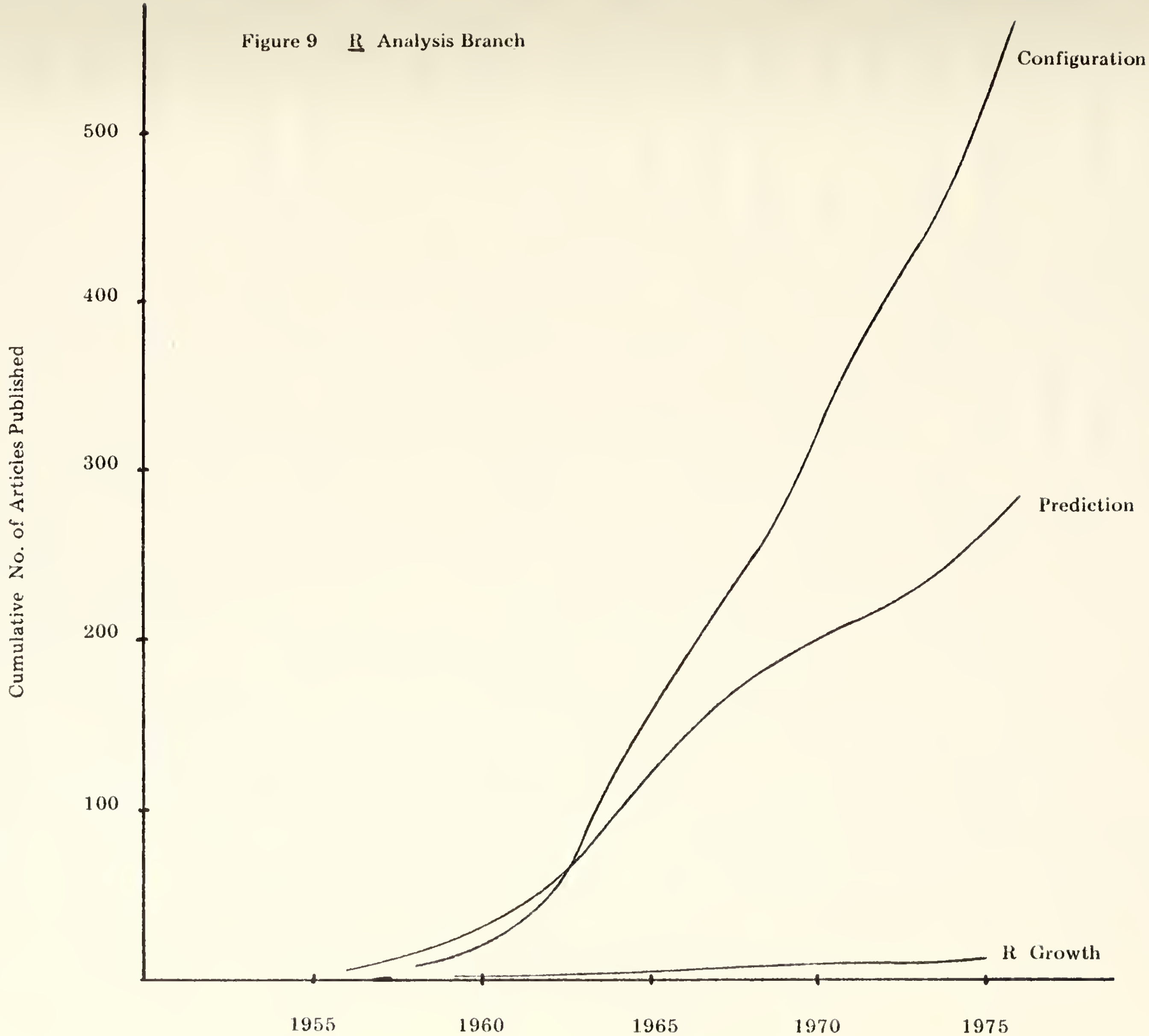
2. Analysis Branch

The literature indicates that the Analysis branch can be split into three subbranches: (1) Configuration, which consists of those analytical techniques dealing with the physical composition of systems of subsystems. (2) Prediction, and (3) Reliability growth. The cumulative growth patterns exhibited in Figure 9 indicate the relative weights given the subtopics in the literature. It is noted that configuration which includes several analysis techniques such as modeling, Failure Modes Effects Analysis (FMEA), Fault Trees, and Reliability Block Diagrams emerged in the mid to late 1950's. It received a large growth stimulus in the early 1960's and then settled into a fairly stable growth pattern which has continued until the present. The early stimulus was primarily due to interest from DOD and NASA, with the power (energy) and the service industries picking up the interest in the 1970's.

Prediction has exhibited characteristics similar to configuration but with somewhat lower emphasis. It too appears to have received increased emphasis in the mid 1970's primarily from DOD and the service industry.

Reliability growth has not shown significant development in comparison to the other subbranches. There has been a small and relatively consistent number of articles each year which have addressed this subject. Most of the articles seem to be concerned with trying to show mathematically whether a product will achieve, or has in fact achieved, a specified reliability level.

Figure 9 R Analysis Branch



Both the Configuration and Prediction subbranches have been further subdivided into twigs. The twigs which have grown out of Configuration are illustrated in Figure 10. Modeling/Simulation and Failure Analysis experienced an extremely sharp increase in growth rate in 1962 and this appears to be primarily due to interest from DOD. The other areas appear to have experienced a reasonably consistent growth pattern. However, Design Review as an analysis technique appears to have matured in the late 1960's. Fault Tree Analysis appears to be receiving increased emphasis in the 1970's. This could be caused by the growing interest in safety, stimulated by the electrical power industry. The technique is presently one of the strong bridges between reliability and safety analysis.

The literature indicates Prediction split into two major areas: Parameter Prediction (estimation) and Probability Distributions. Each of these twigs received impetus about 1960 (see Figure 11) which resulted in an increased growth rate. Parameter Prediction has sustained the increased growth rate occurring in the early 1960's. However, there is indication of a decrease in growth of Probability Distributions after 1965 in comparison with the other twig. Maturity has not yet occurred, although the trend indicates that it is probably not far off.

The third area under Prediction, Apportionment, emerged in 1961, flourished for several years, and then appears to have died off in the late 1960's.

Figure 10 Configuration Subbranch

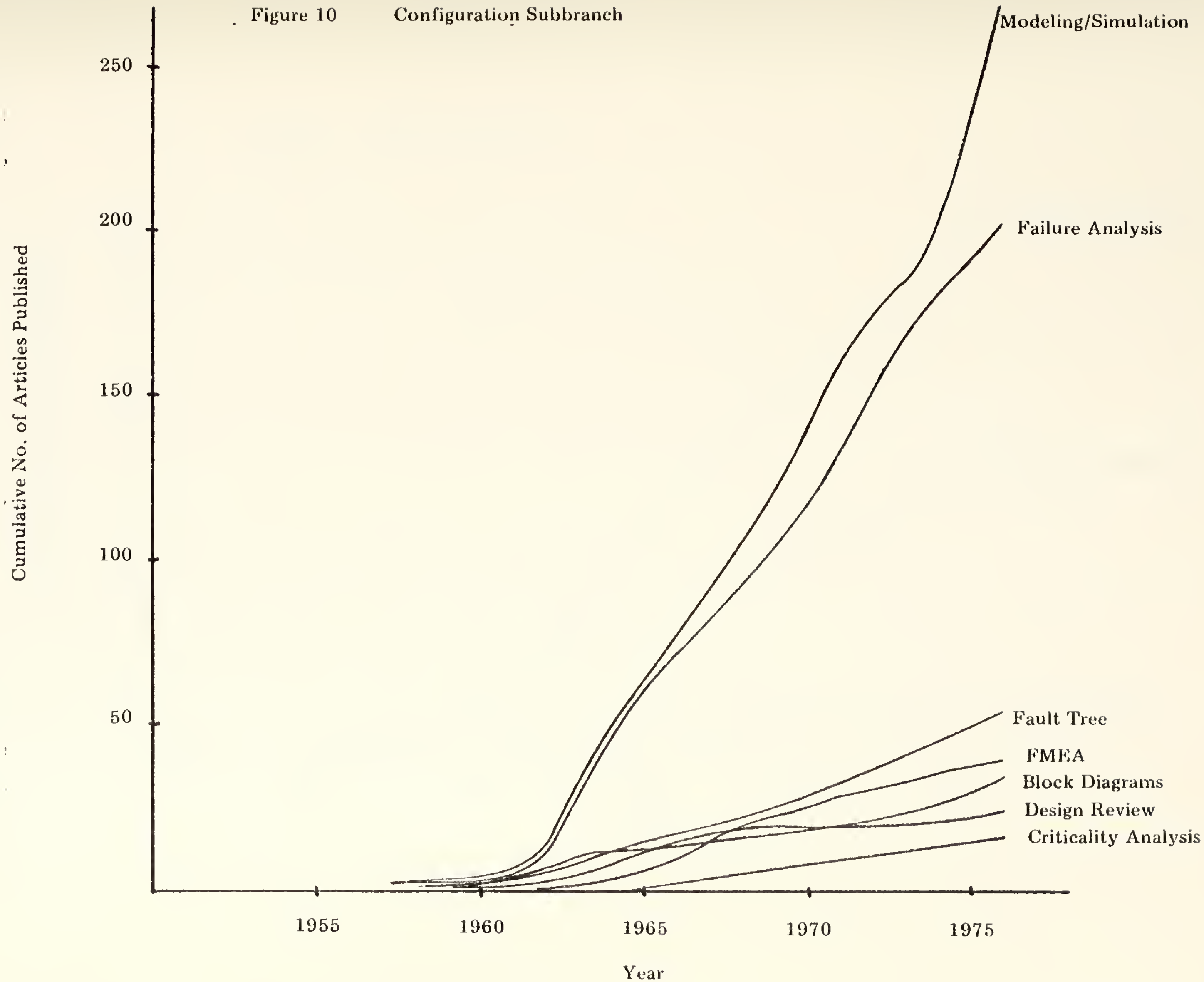
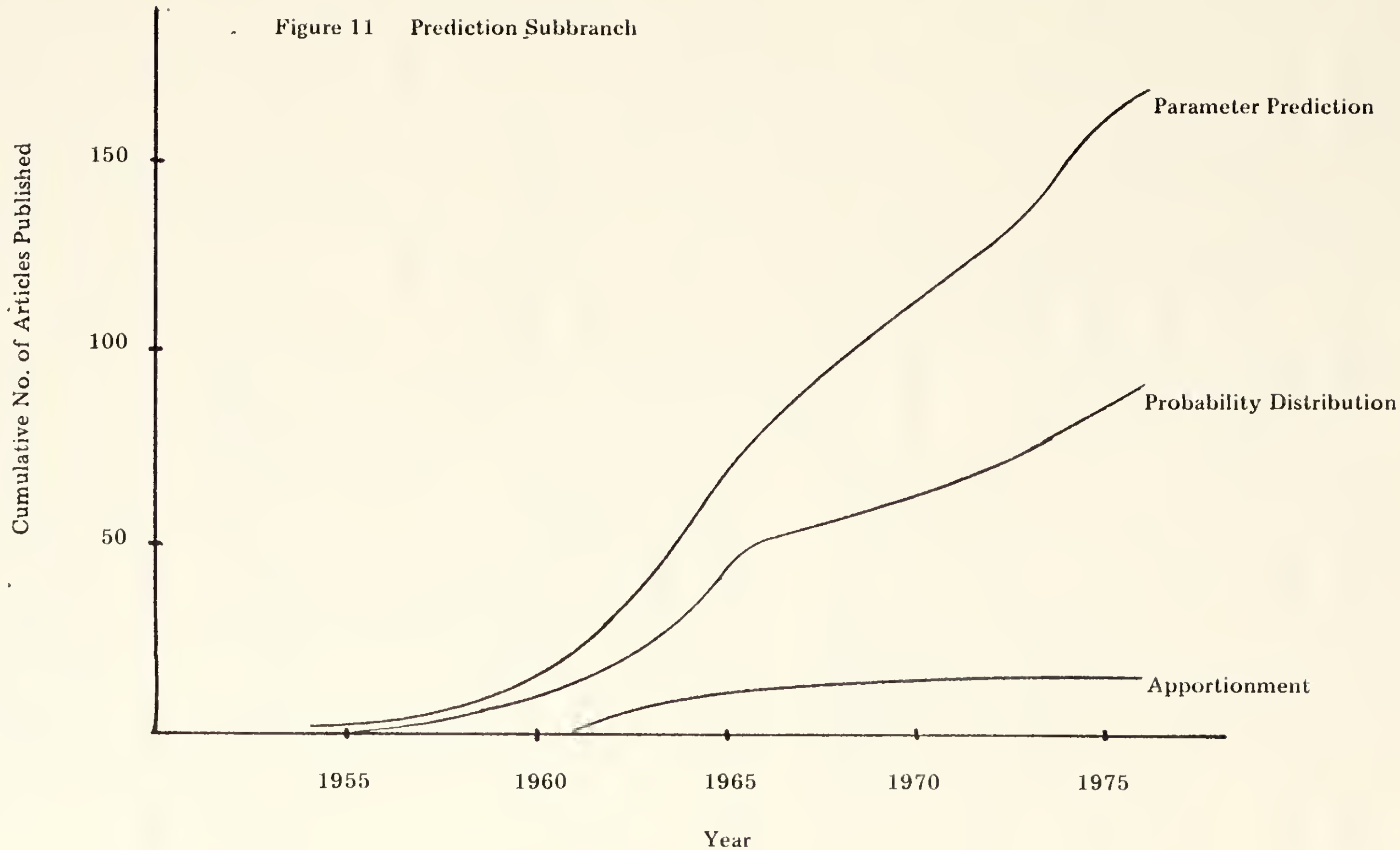


Figure 11 Prediction Subbranch



3. Management Branch

This branch is very broad in scope and is the most complex to discuss since numerous subbranches and twigs have emerged since the 1950's. Figure 12 depicts the structural development of this branch using the tree analogy.

Figure 12 is intended to display the structural relationships of the Management branch without trying to introduce the time dimension into the illustration.

The major subbranches of Management are illustrated in Figure 13. All of the subbranches and twigs, with the exception of Product Liability, have received major impetus to their growth from DOD and NASA.

The Reliability Program Management, Cost, Failure Recurrence Control, and Procurement subbranches all emerged very early in the literature. As noted in Figure 13, Reliability Program Management has received far more emphasis than any of the other subbranches. This subbranch received a major impetus from DOD in the early 1960's and the increased growth pattern has carried on into the early 1970's. There are indications that it may be approaching maturity because of the economic cut-backs mentioned in Chapter II. The other main subbranches, Failure Recurrence Control, Procurement, and Cost appear to be exhibiting fairly consistent growth patterns. Failure Recurrence Control (efforts by Management to curtail and/or preclude recurrence of reliability failures) is indicating signs of approaching maturity in the mid-1970's, whereas both Procurement and

Figure 12 R Management Branch Structure

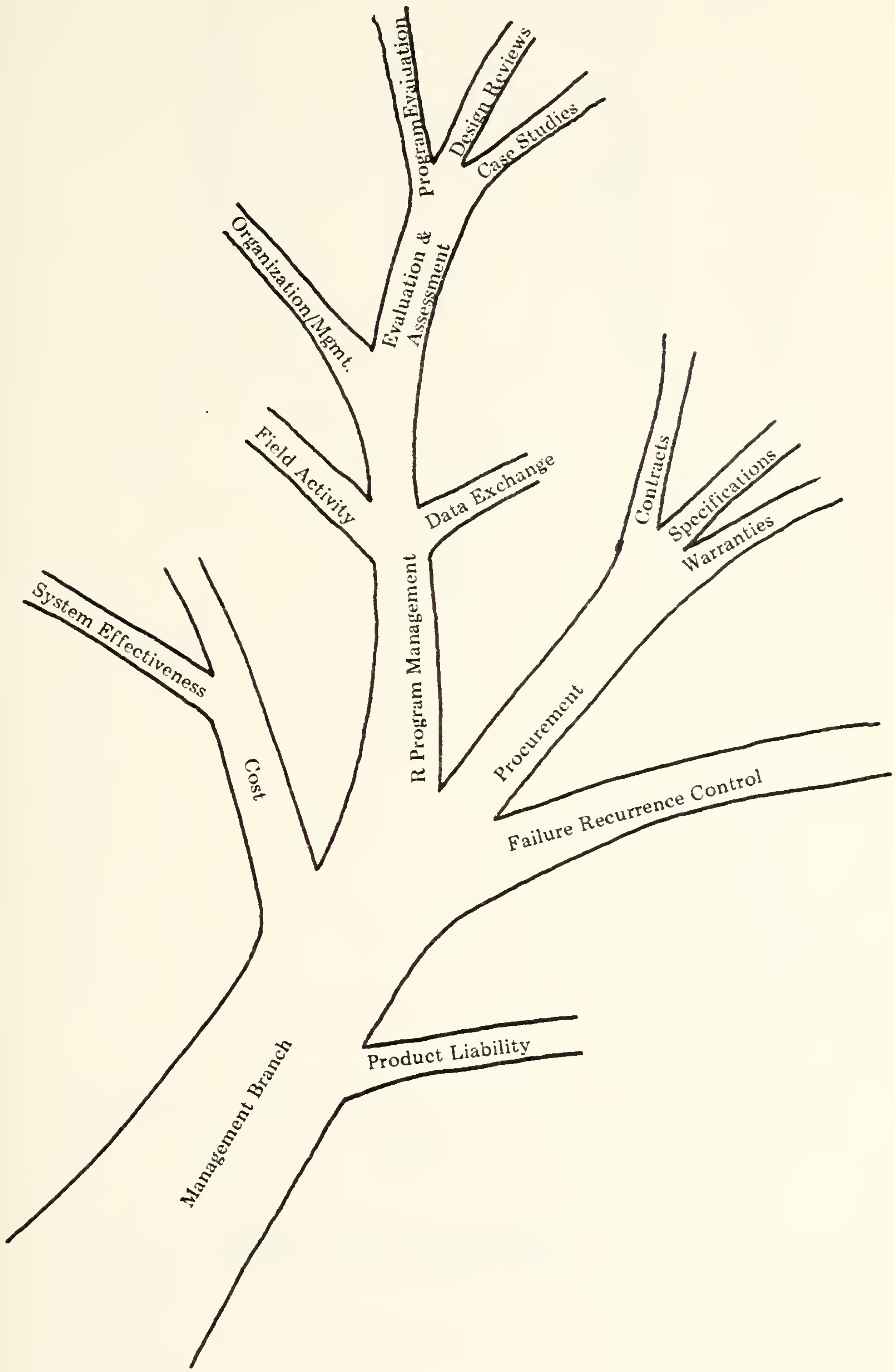
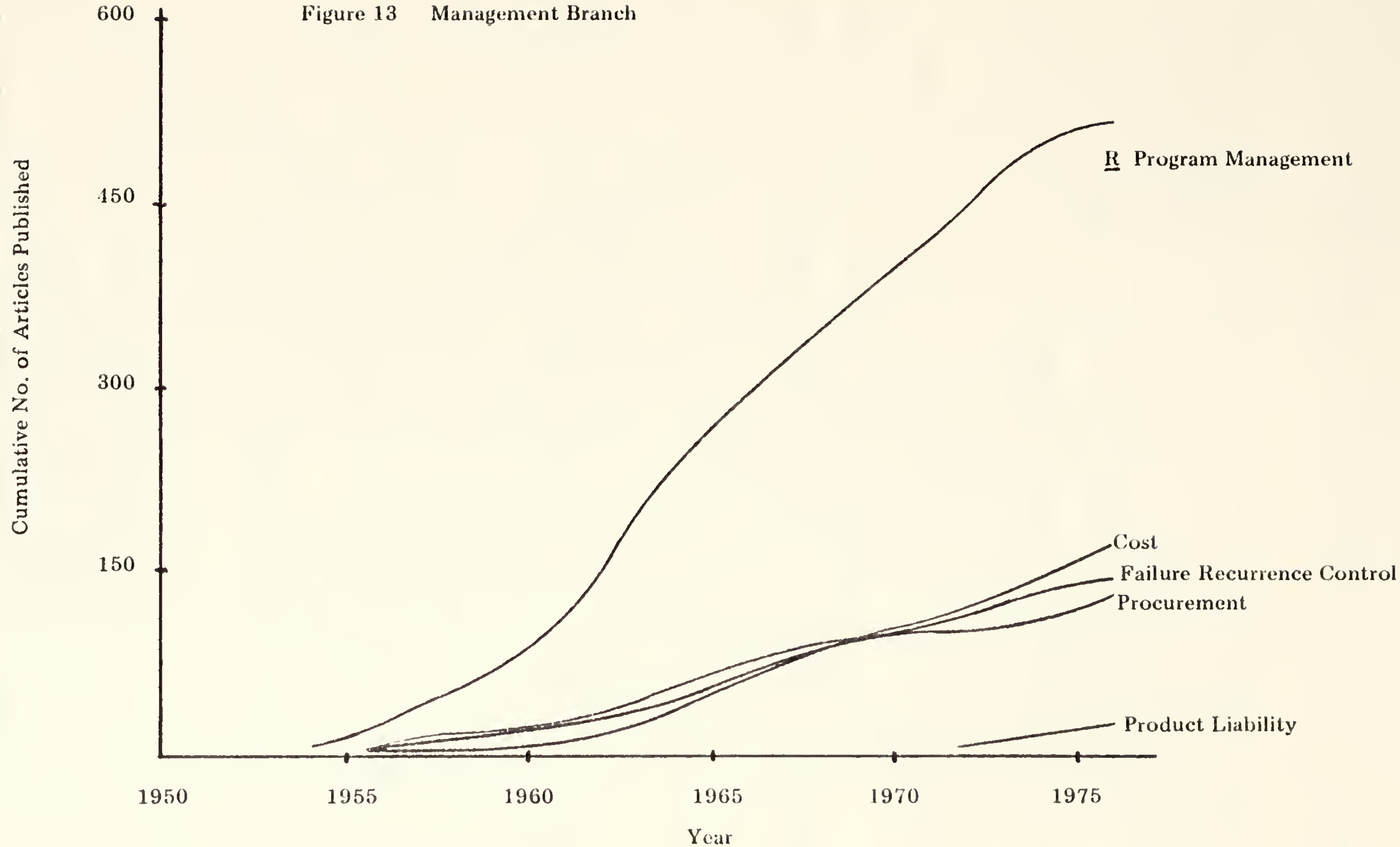


Figure 13 Management Branch



Cost are showing signs of increasing emphasis. This is especially true of the twig, Systems Effectiveness, shown in Figure 14.

Systems Effectiveness emerged in the early 1960's and has established and maintained a very healthy growth pattern to the present. This area has been primarily driven by DOD, and it is expected that this emphasis will continue, at least in the foreseeable future. Product Liability emerged in the early 1970's and is giving every sign of growing into a major area in the near future.

The main subbranch, Reliability Program Management, has developed several twigs, and their growth patterns are illustrated in Figure 15. All of these areas have sustained fairly consistent growth patterns with the exception of Training/Education which appears to have reached maturity in the mid 1970's. Field Activity emerged in the mid-1960's and has only recently experienced some growth.

Evaluation and Assessment can be further split into three twigs as shown in Figure 16. It can be noted that all three of these areas have received added emphasis in the early 1970's.

Procurement, the remaining subbranch of Management to be discussed, has generated three major twigs as illustrated in Figure 17. The growth patterns for specifications and contracts exhibit somewhat similar characteristics with both having received stimulus in the mid 1960's and much less emphasis in the early 1970's. Data from the last couple of years, however, indicates renewed emphasis in these areas

Figure 14 System Effectiveness

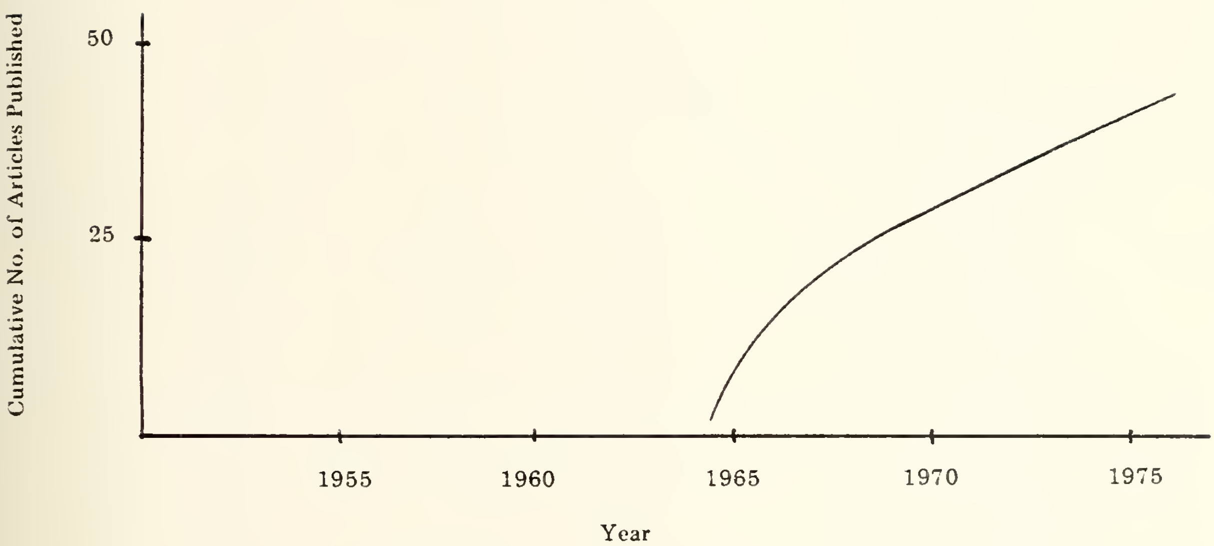


Figure 15   R Program Management

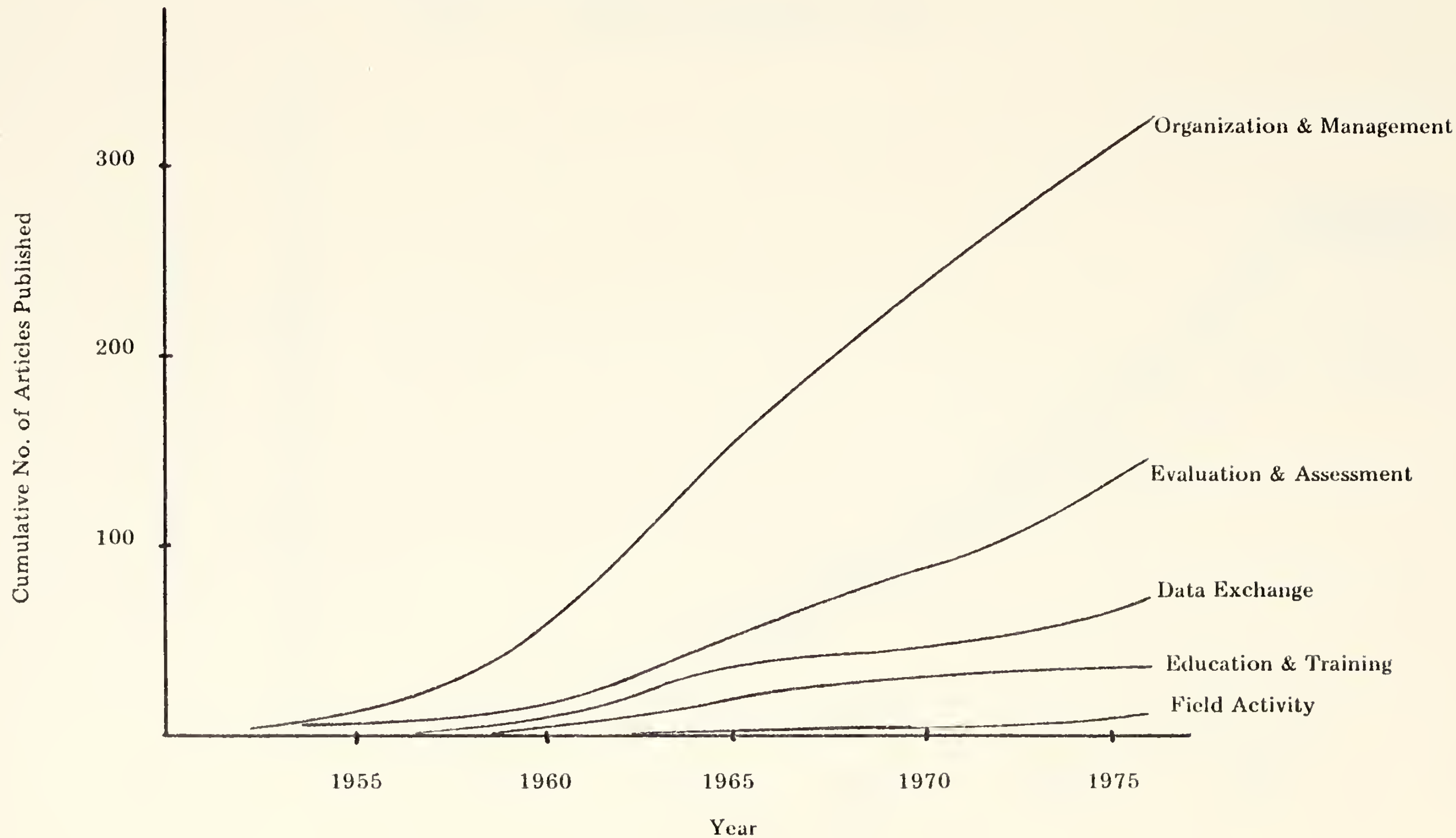


Figure 16 Evaluation & Assessment Subbranch

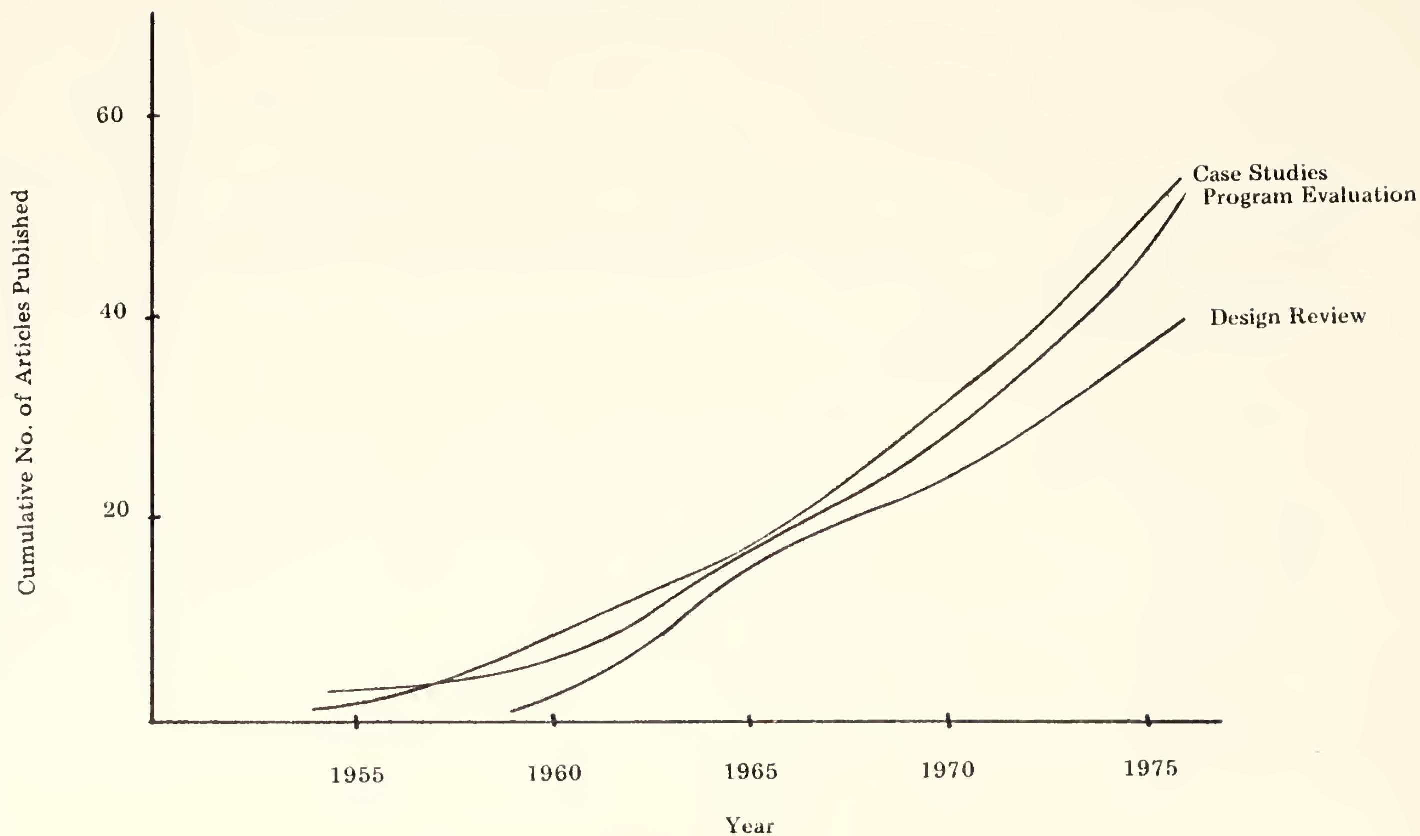


Figure 17 Procurement Subbranch

primarily from DOD and the service (utilities, airlines, etc.) industries. Warranties emerged in the late 1950's and continues to exhibit a pattern of increased growth.

4. Test and Evaluation Branch

The Test and Evaluation (T & E) branch, illustrated in Figure 18, is split into three main subbranches: Methods (of testing), Statistics, and Reporting/Evaluation. There appears to have been greater emphasis given to Methods than either of the other two subbranches. This emphasis seems to have occurred in the early 1960's and the resulting growth pattern has continued on into the present. The T & E branch emerged in the earliest literature and appeared to be an extension of the Quality Control (QC) discipline. The literature gradually transitioned from Quality Control related issues into Reliability during the 1950's. The combined influence of DOD and NASA appear to be the major motivation for the rapid increase noted for Methods of Testing during the early 1960's.

Statistics was definitely a carry over from Quality Control and development of several twigs in this subbranch are noted in the literature. These are illustrated in Figure 19. Sampling Plans and Design of Experiments are the most direct carry overs from Quality Control and it appears that Design of Experiments has matured in the mid 1970's. Bayesian techniques and Parameter Estimation have exhibited the most active growth patterns. Parameter Estimation had exhibited a relatively mild growth rate until 1970, at which point it appears to have received added

Figure 18 R Test & Evaluation Branch

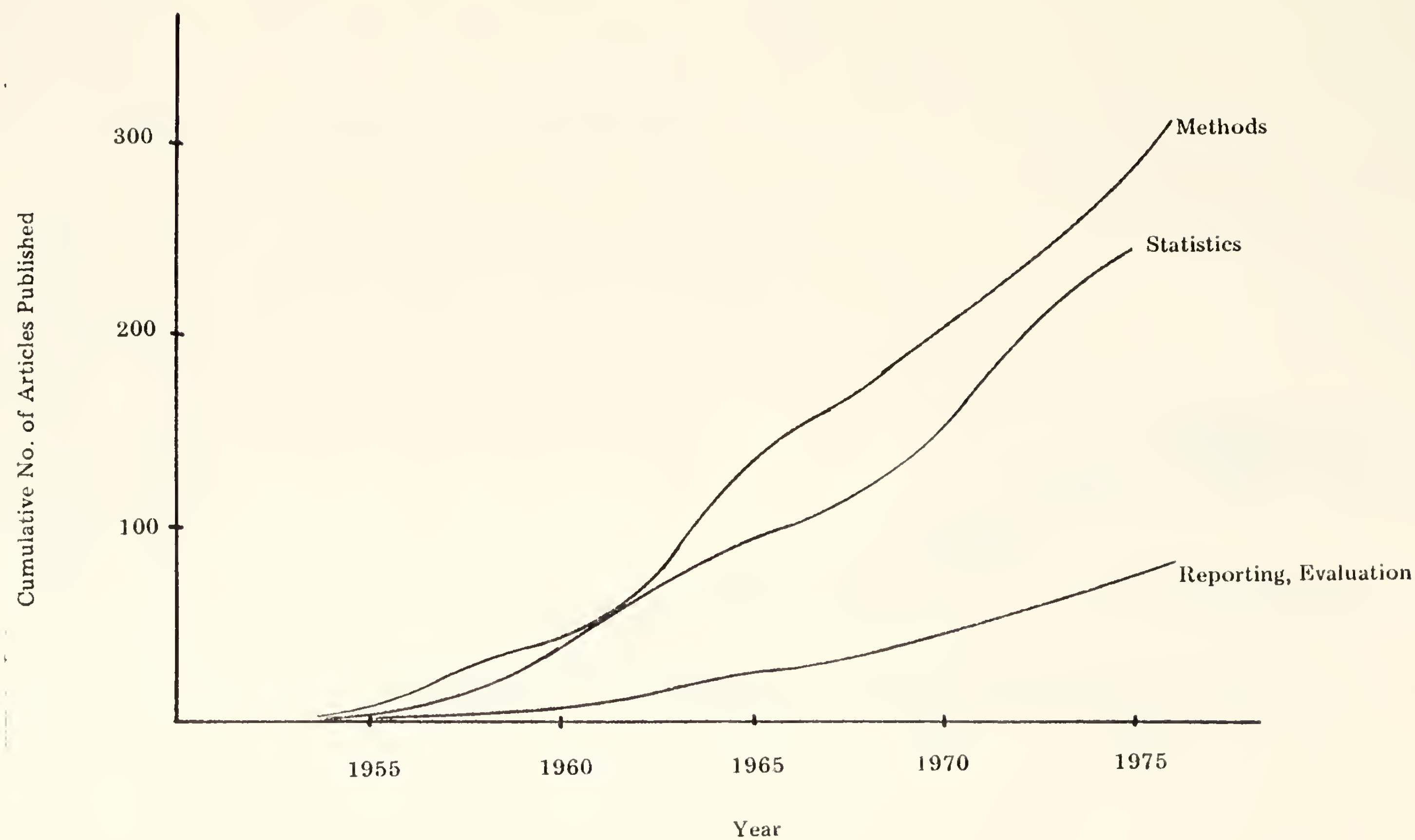
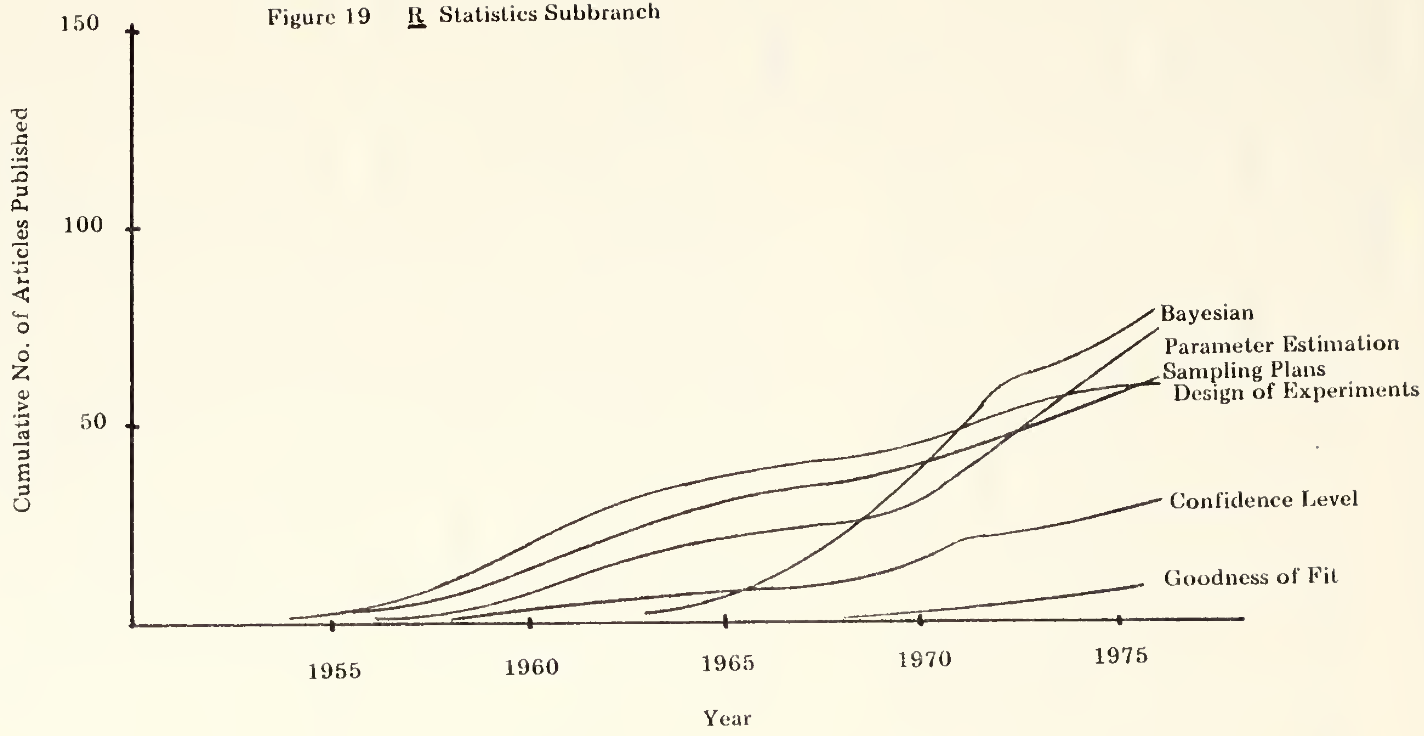


Figure 19 R Statistics Subbranch



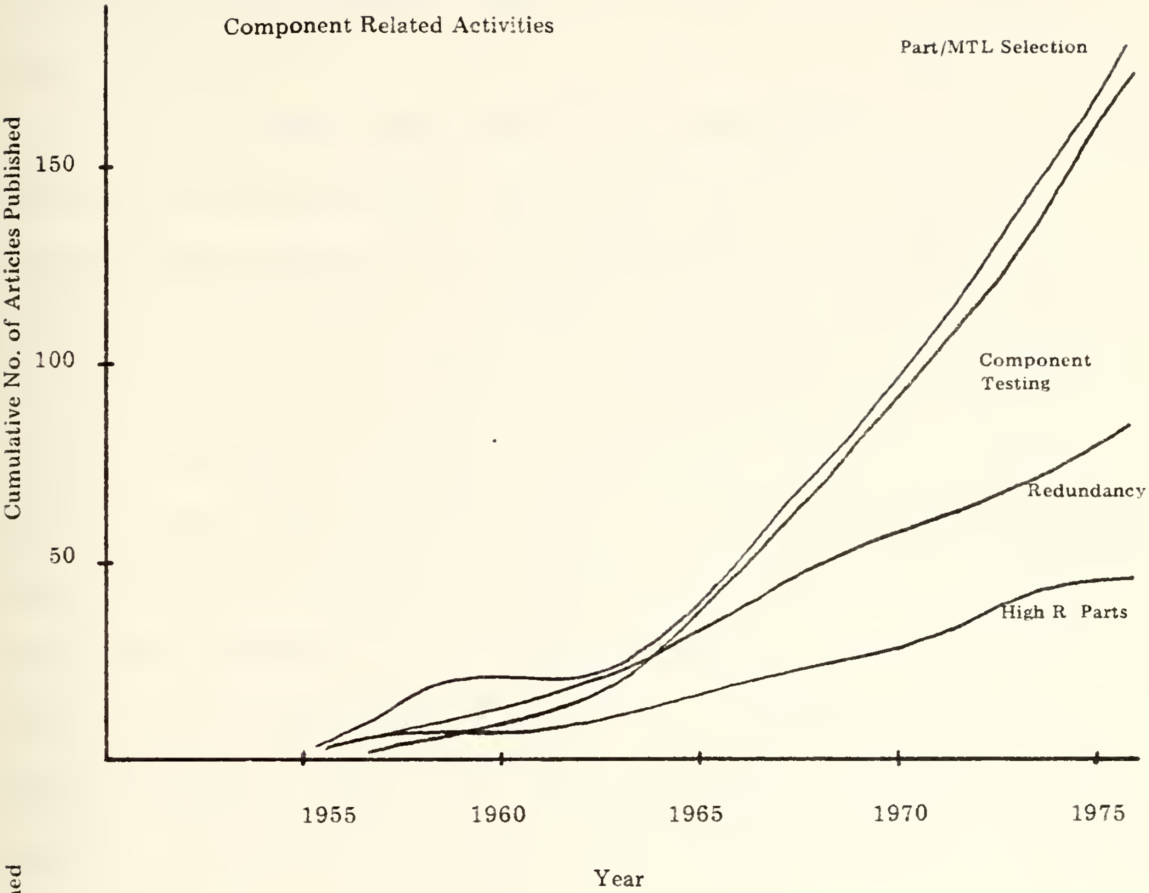
emphasis. This seems to correlate with the increased attention from the service industries, especially the Power Industry, to testing in general.

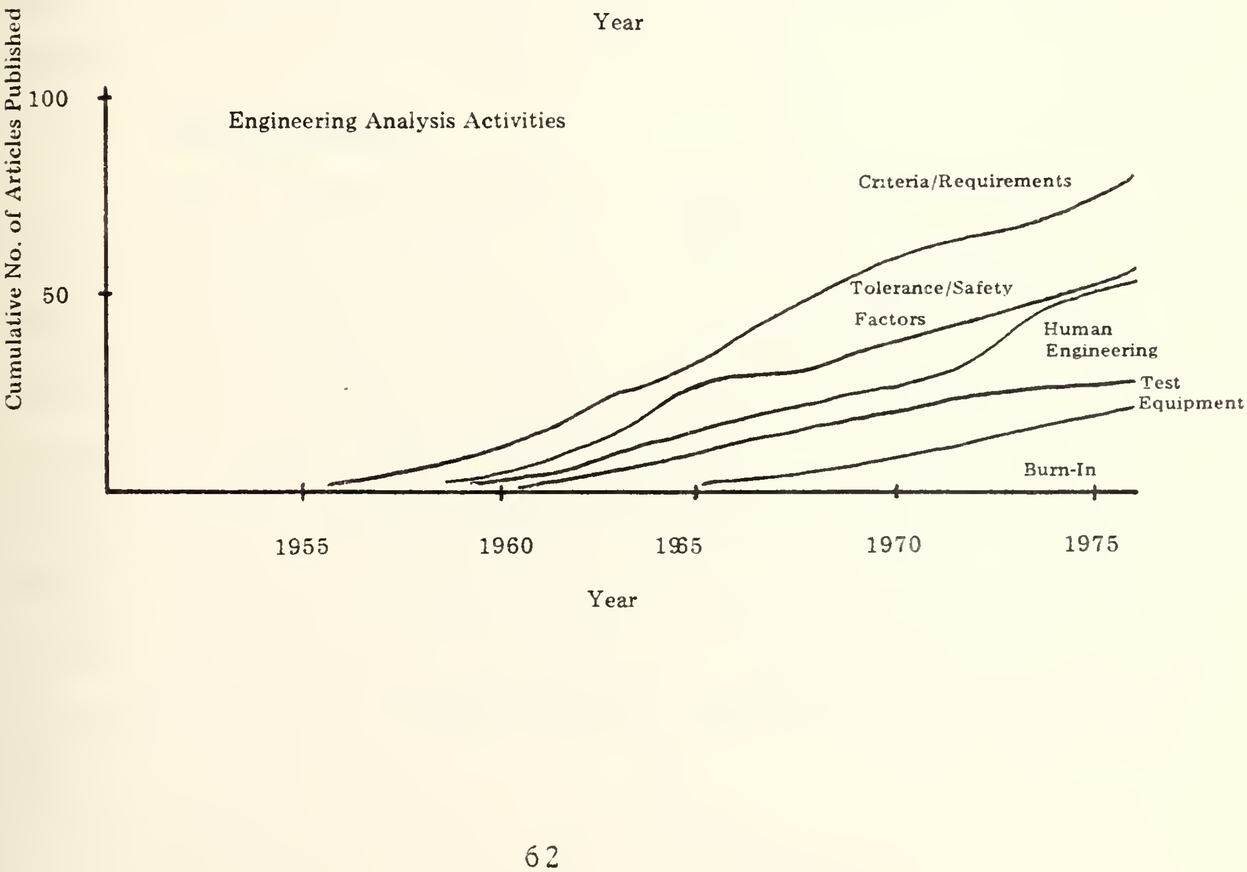
Bayesian techniques emerged about 1963 and exhibited a rapidly increasing growth pattern until about 1972 when it dramatically decreased, but seems to be picking up again. The reasons underlying this are not identified at this point. The other twigs, Confidence Level and Goodness of Fit, have exhibited low growth characteristics, and there is insufficient data available to comfortably project future activity in these areas.

5. Design Branch

This branch has produced several twigs which, for classification purposes, have been treated as separate entities. Design has been split into component related activities and engineering analysis activities to separate the curves for ease and clarity of data presentation. This data is presented in Figure 20. From the upper portion of Figure 20, it can be noted that Part/Material Selection and Component Testing have been the most active areas in this branch. Both of these twigs exhibited dramatic increases in growth starting about 1964, and the increased growth rate has continued to the present. The sharp increase in growth appears to have been initiated by interest from NASA and later sustained by both DOD and NASA. The other two areas, Redundancy and High Reliability Parts, have exhibited much lower growth patterns. In fact, High Reliability Parts appears to have reached maturity. Redundancy appears to

Figure 20 R Design Branch





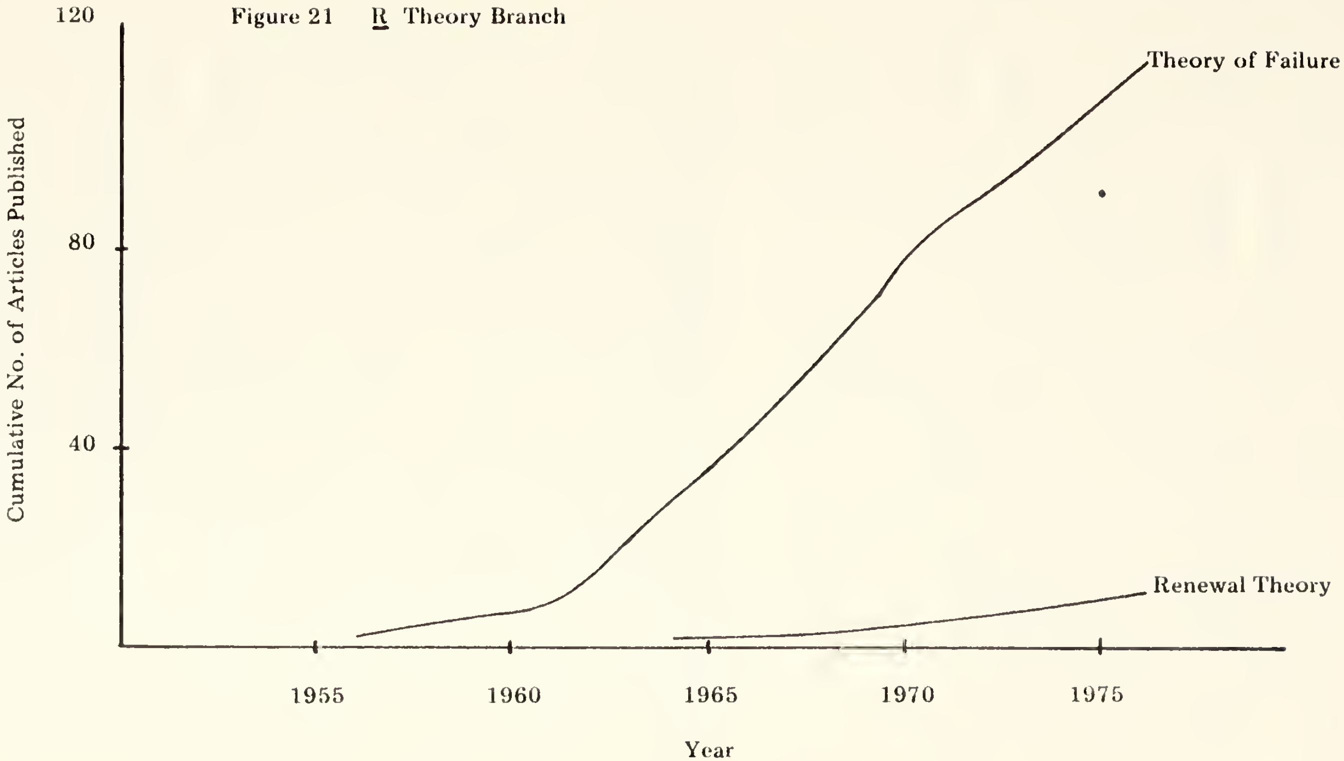
be receiving increased emphasis in the mid 1970's and this seems to be primarily due to articles concerned with reliability in the Mars Probe and Space Shuttle (space applications).

The other twigs which have developed from the Design Branch are presented in the lower portion of Figure 20. Criteria/Requirements and Tolerance/Safety factors have exhibited reasonably consistent growth patterns since they emerged in the mid 1950's. Tolerance/Safety factors received a surge of interest in the mid 1960's but soon settled back into its previously established growth pattern. Test equipment emerged in 1960 and appears to have received consistent emphasis until the mid 1970's at which point it seems to have matured. Perhaps it is being presented in other formats. There has been relatively consistent discussion in the literature of burn-in since about 1965 to the present.

6. Theory Branch

This branch discernibly emerged in the literature in the mid to late 1950's. The primary focus appears to be Theory of Failure and this subbranch has exhibited a relatively constant growth pattern since the sharp increase in slope in about 1961, (see Figure 21). Renewal Theory as applied in this context, has emerged as a twig in the early 1960's and has exhibited a fairly consistent growth pattern to the present. Renewal theory, as treated in the literature, is another of the bridges between reliability and maintainability.

Figure 21 R Theory Branch



7. Data Branch

The Data Branch has received the least emphasis of all the main branches of the reliability discipline. However, it has demonstrated a reasonably consistent growth pattern, as shown in Figure 22. This branch has produced two major twigs, Data Collection and Data Processing/ Utilization. Both twigs emerged very early in the 1950's and exhibited a fairly constant growth pattern until 1969 or 1970 at which point the growth curves show an increasing slope. This trend seems to be resulting from increased emphasis by both DOD and the service industries on the subject of making effective use of data for both reliability and maintainability analysis, prediction, allocation, and spare parts determination.

8. Reliability Branch Correlation with Specific Applications

Articles which could be classified along the application dimension as well as along the reliability intradiscipline dimensions have been retained in the computer stored data base and provisions were made to retrieve these articles by requesting the appropriate combination of keywords. This has provided a good mechanism for correlating the growth of the more active branches with specific applications of the techniques contained within the branches. Only the four most active branches (Design, Analysis, Management, and Test) have been selected for correlation because these reflect the major emphasis of the reliability discipline and, hence, contain sufficient data to establish some meaningful trends. Figure 23 presents the correlations of Design and

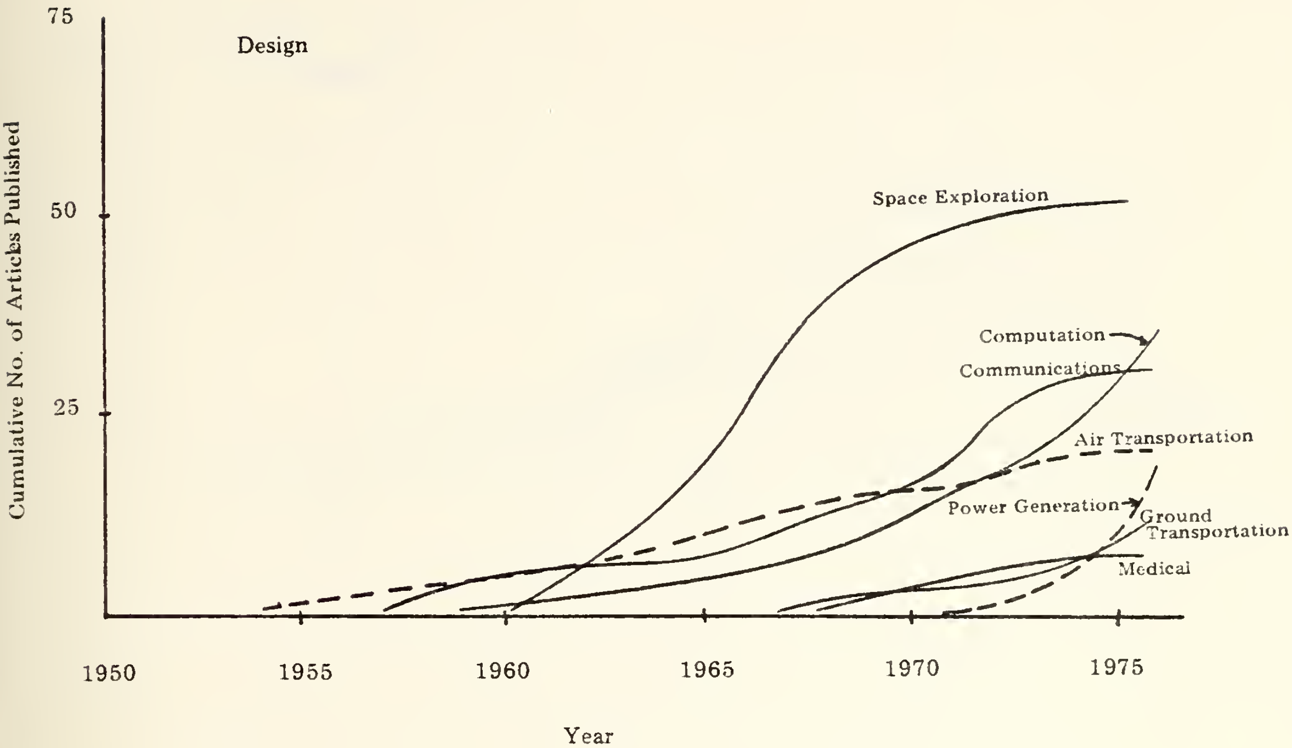
Figure 22 R Data Branch

Analysis with specific applications. Figure 24 presents Management and Test methods also correlated with specific applications.

In Figure 23, the curves correlating Design with specific applications indicate some rather dramatic changes in emphasis of this branch over the last two decades. Design applied to Space Transportation has received more emphasis than any other application during the 1960's and then it appears to have matured in the 1970's. Air Transportation design applications were mentioned in the earliest literature, and it has displayed a relatively constant growth rate until the mid 1970's when it seemed to approach maturity. Communication and Medical Applications also seem to be approaching maturity in the mid 1970's after having experienced fairly heavy emphasis in the late 1960's and early 1970's. Computer Applications (including both software and hardware) emerged in the literature in the late 1950's and has experienced increasing emphasis ever since. Ground Transportation (primarily rapid transit) emerged in the mid 1960's and is experiencing increasing emphasis in the mid 1970's. Power Generation (includes both nuclear and conventional) emerged in the early 1970's and is showing signs of phenomenal growth during the 1970's if the present trend continues.

The lower set of curves in Figure 23 indicates the relative emphasis which Analysis has had in various applications. The same general trends are evident in this branch as were noted for the Design branch. However, it appears

Figure 23 Correlation of Design and Analysis with Specific Applications



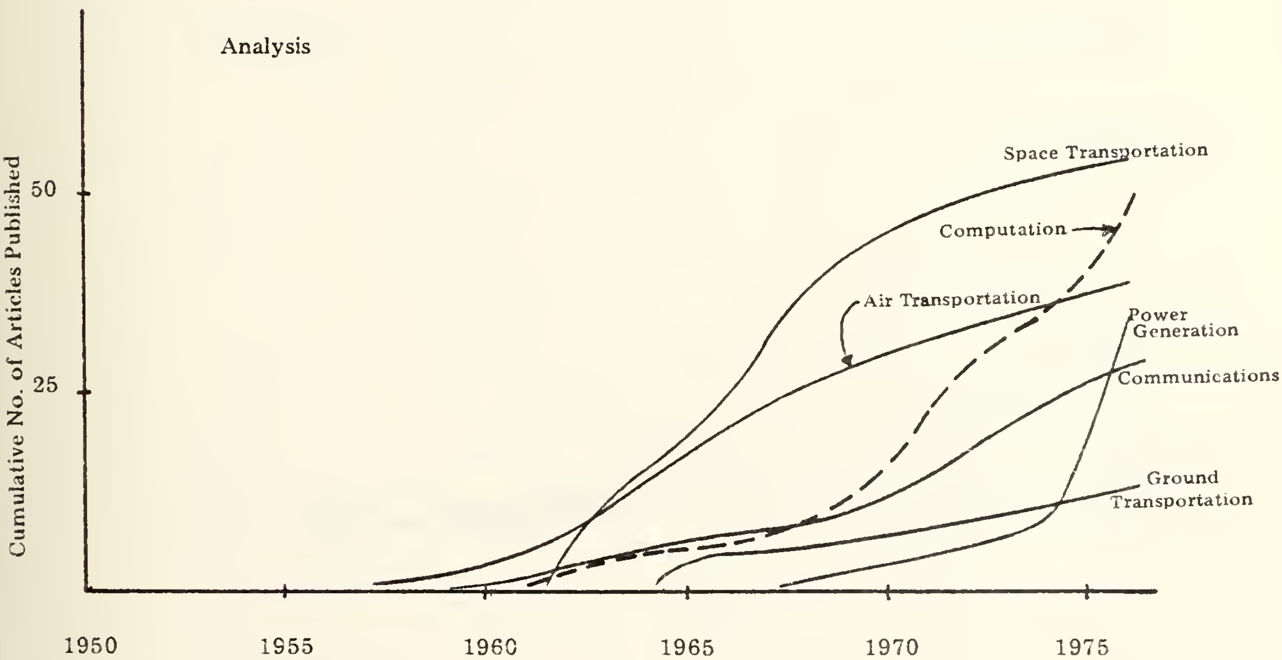
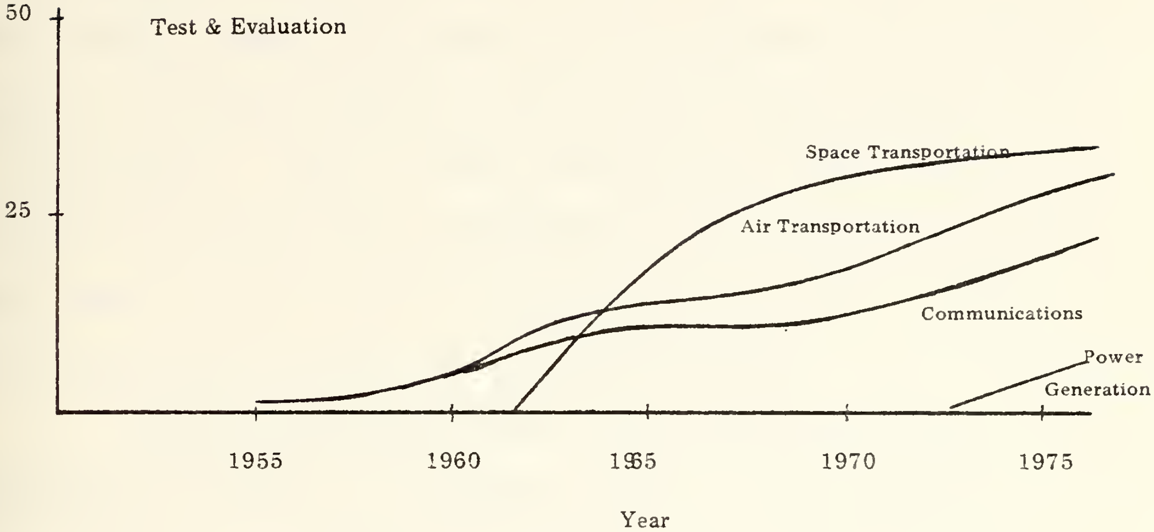
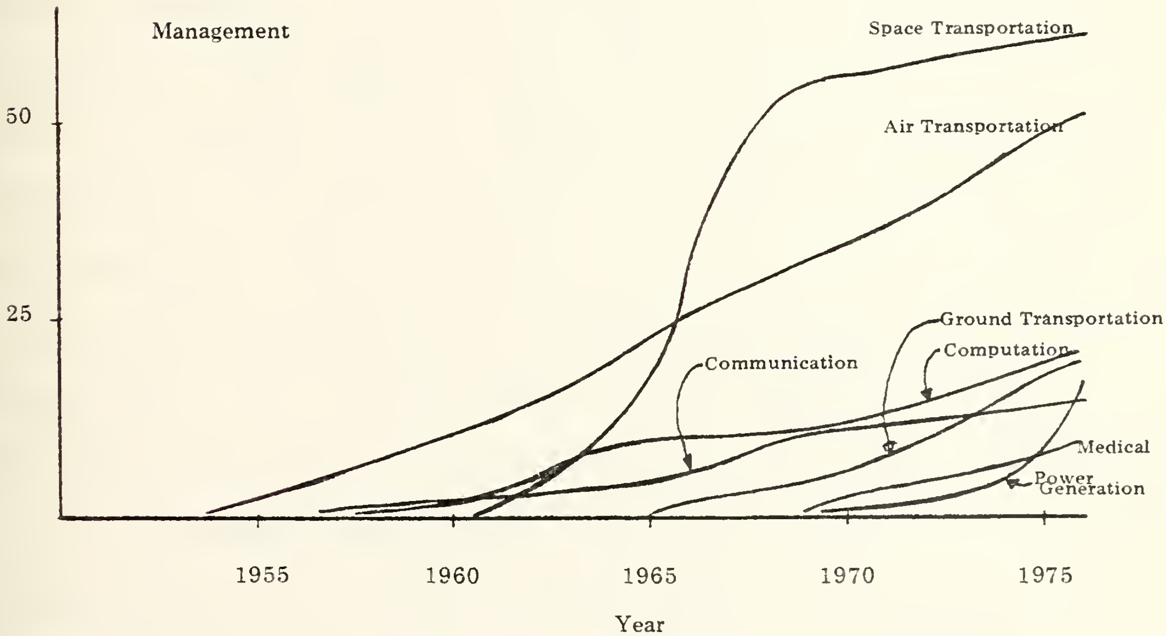


Figure 24 Correlation of T & E and Management with Specific Applications





that Analysis has lagged Design by two or three years. There does not appear to be any Analysis applications that have matured, although Space and Air Transportation are exhibiting signs that this may happen in the not too distant future. Analysis applications emphasis, like Design, appears to have shifted to Computer and Power Generation in the 1970's. Both of these application areas have received very high growth stimulation in the last few years and there is every reason to believe that these trends will continue, at least in the near future.

Figure 24 presents the Test & Evaluation and Management branches correlated with the same specific application areas discussed earlier for the Design and Analysis branches. Some of the trends established for Analysis and Design are also evident in Figure 24. For example, Space Transportation applications has clearly reached maturity in the early 1970's for both T & E and Management. Other applications presented in the T & E portion of Figure 24 all indicate stable growth patterns in the 1970's. T & E application in the Power Generation field emerged in the mid 1970's and is in such an infant state that trend prediction will not be attempted now except that, it is likely that it will experience significant growth because of the increase in the other branches.

Management applications other than Space Transportation and Communications appear to be exhibiting strong, stable growth patterns. Ground Transportation emerged in the mid 1960's and has achieved a strong growth

pattern (most of the emphasis here has been in rapid transit considerations for cities). Power Generation has again taken off with every indication of establishing a very strong growth pattern.

Management applications in the Medical Field emerged in the late 1960's and appears to have established a stable growth pattern. A large part of the emphasis here has dealt with the effect of medical device failures on patient safety.

9. Reliability Branch Correlations with General Applications

Throughout the preceding discussions of the evolution of the reliability discipline, several statements have been made concerning factors and organizations which have provided major stimulus to reliability growth. Data which support these statements are presented in Figure 25 and Figure 26. These data are presented in the form of densities instead of the cumulative format, in order to gain an insight into the emphasis that particular organizations have placed on the major Reliability branches at any given point in time.

Figure 25 indicates the correlation of the Analysis and Design branches with selected general application categories. The top curve (double thickness) in each plot represents the overall density of articles which addressed Analysis or Design regardless of application. The cross hatched areas under these curves represent the emphasis placed by various organizations at various points in time. For example, in the Analysis portion of Figure 25, it can

Figure 25   Correlation of Analysis & Design with General Applications

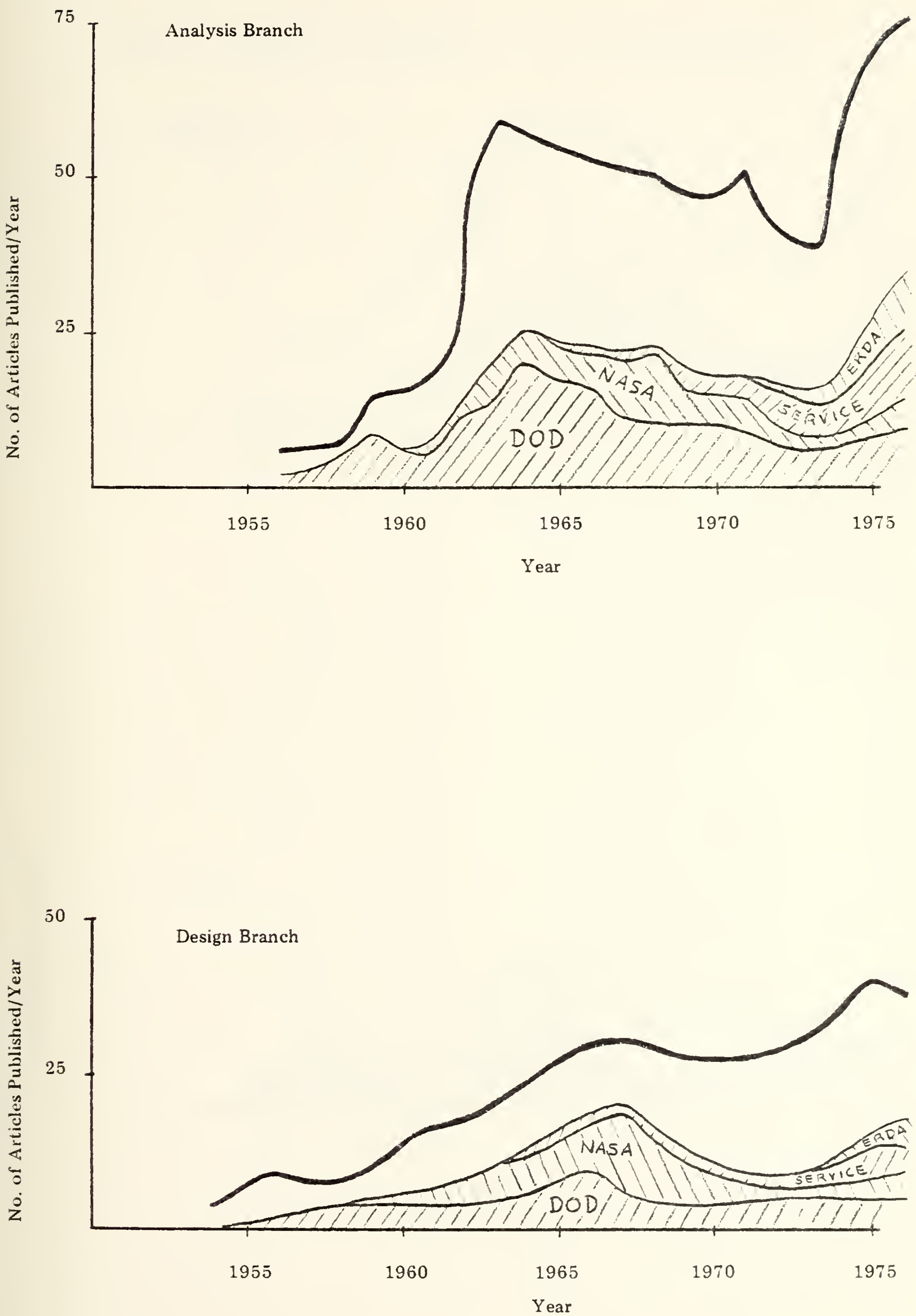
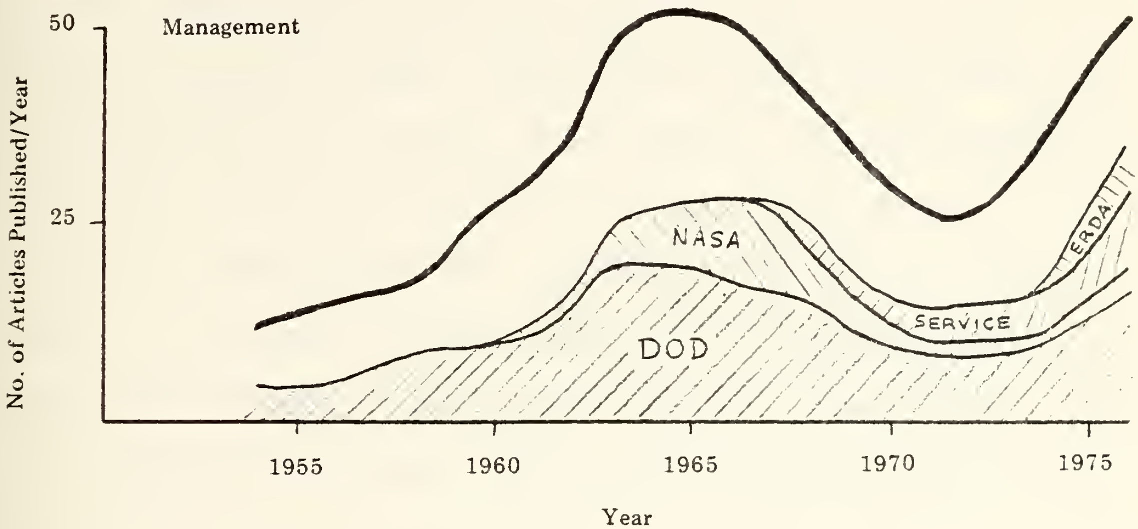
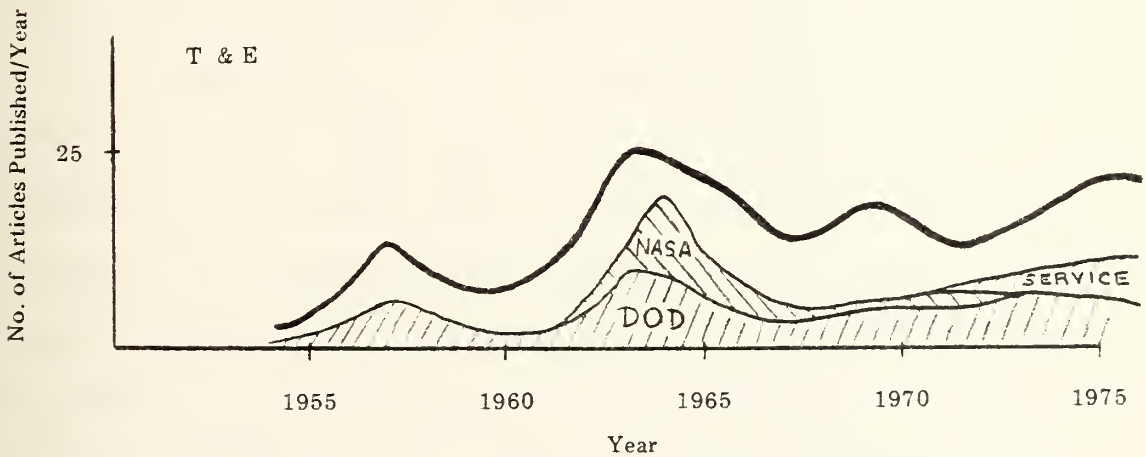


Figure 26 Correlation of Management and T & E with General Applications





be noted that DOD's emphasis on Analysis peaked in the mid 1960's and declined thereafter until the mid 1970's. Service industries (which include airlines, utilities, telephone companies, etc.) began emphasizing Analysis in the mid 1960's and have progressively increased their interest to the present. ERDA began emphasizing Analysis in the early 1970's, also with steadily increased emphasis. The trends noted for Analysis are typical of those established by the other main branches. There are minor shifts in time when various branches were emphasized by either DOD or NASA, however the general trends appear consistent for the four branches analyzed in Figures 25 and 26.

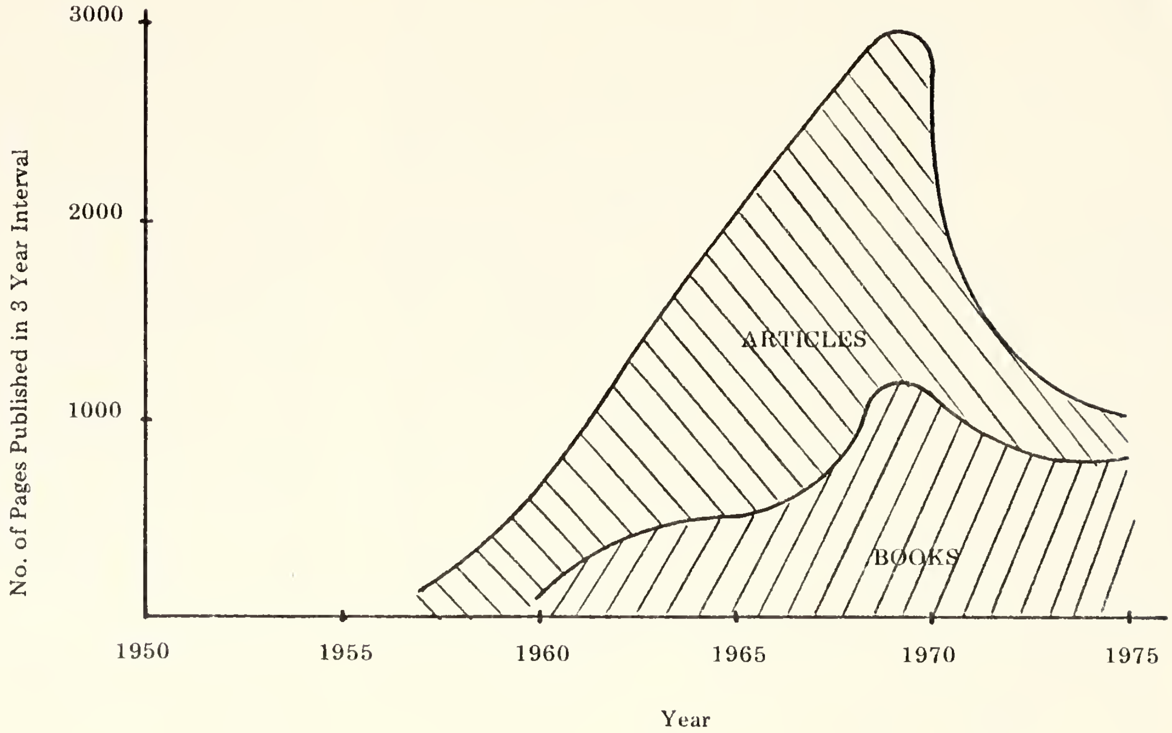
Correlations of these branches were also run with the other general application areas indicated in the taxonomy. There was very low activity in all of the other areas with the exception of consumer capital items. This application has received steadily increasing emphasis in both analysis and design activity for the last two years. The literature surveyed does indicate, though, that DOD applications are beginning to place renewed emphasis on Management in the mid 1970's. The literature indicates that this is probably due to increased awareness of the magnitude of their Operations and Maintenance Budget and the impact that reliability of equipment in the field has on this budgetary item. These same considerations have also provided a good deal of impetus to the growth of the maintainability discipline as described in the next section.

D. MAINTAINABILITY DISCIPLINE GROWTH

A composite picture using both books and short articles was formed in order to gain a perspective of the overall discipline growth. Figure 27 represents this composite overview. Again, the unit of measure for this comparison is the number of pages published in a three year interval.

Figure 27 indicates that interest in maintainability began about 1957, sharply increased to about 1966, and then dramatically decreased until about 1972. The decline noted in the 1970's could be the beginning sign of a maturing discipline or it could be due to a shift in interest away from maintainability towards greater emphasis on reliability. The growth in complexity of systems led to the realization that equipment reliability could not be improved to the extent that the need for maintenance could be economically eliminated. Although the search for further reliability improvement continued, it became unwise to plan future systems without considering maintainability in the design. The significant increases in operating and support costs provided additional support for the rising interest in maintainability. This increase in costs occurred while developing agencies were working with increasingly limited funds. The overall growth of Maintainability was strongly influenced by recognition of this engineering discipline as a critical element in system effectiveness by the military.

Figure 27 M Discipline Emphasis



E. MAINTAINABILITY INTRADISCIPLINE GROWTH

This analysis was conducted by plotting the cumulative number of articles published on selected topics of maintainability as described earlier.

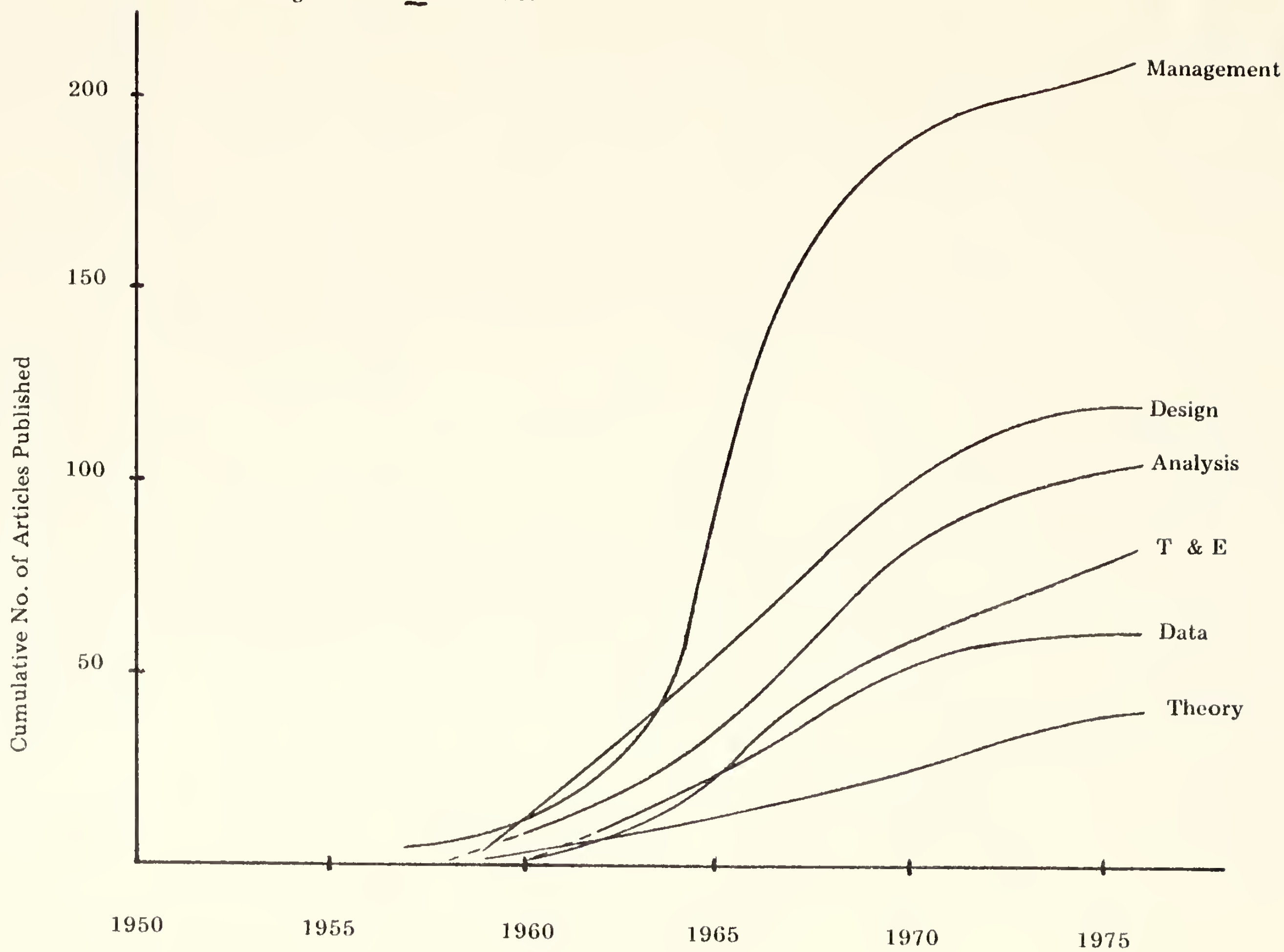
1. Maintainability Branch Growth Trends

The curves in Figure 28 indicate that management has received far more emphasis than any of the other branches. This emphasis in management stems from the imposition of firm military standards on all DOD contracts beginning in the late 1960's. Analysis and Design emerged in the 1950's when maintainability criteria were being developed. Their growth then increased as maintainability requirements became better defined in the early 1960's. Analysis and Design seem to have matured in the 1970's.

Data growth rose in the early 1960's, began flattening out in the late 1960's and appears to have matured in the 1970's. The rise appears to be primarily due to the military standard that directs the contractor to establish data collection, analysis, and corrective action systems.

Maintainability Test & Evaluation emerged in the late 1950's, rose slowly in the middle 1960's and then has increased to the present. The growth increase noted in the late 1960's appears to be derived from the military requiring maintainability demonstration tests by the contractor. Growth tendencies within each of the above main branches are developed in the following sections.

Figure 28 M Branches



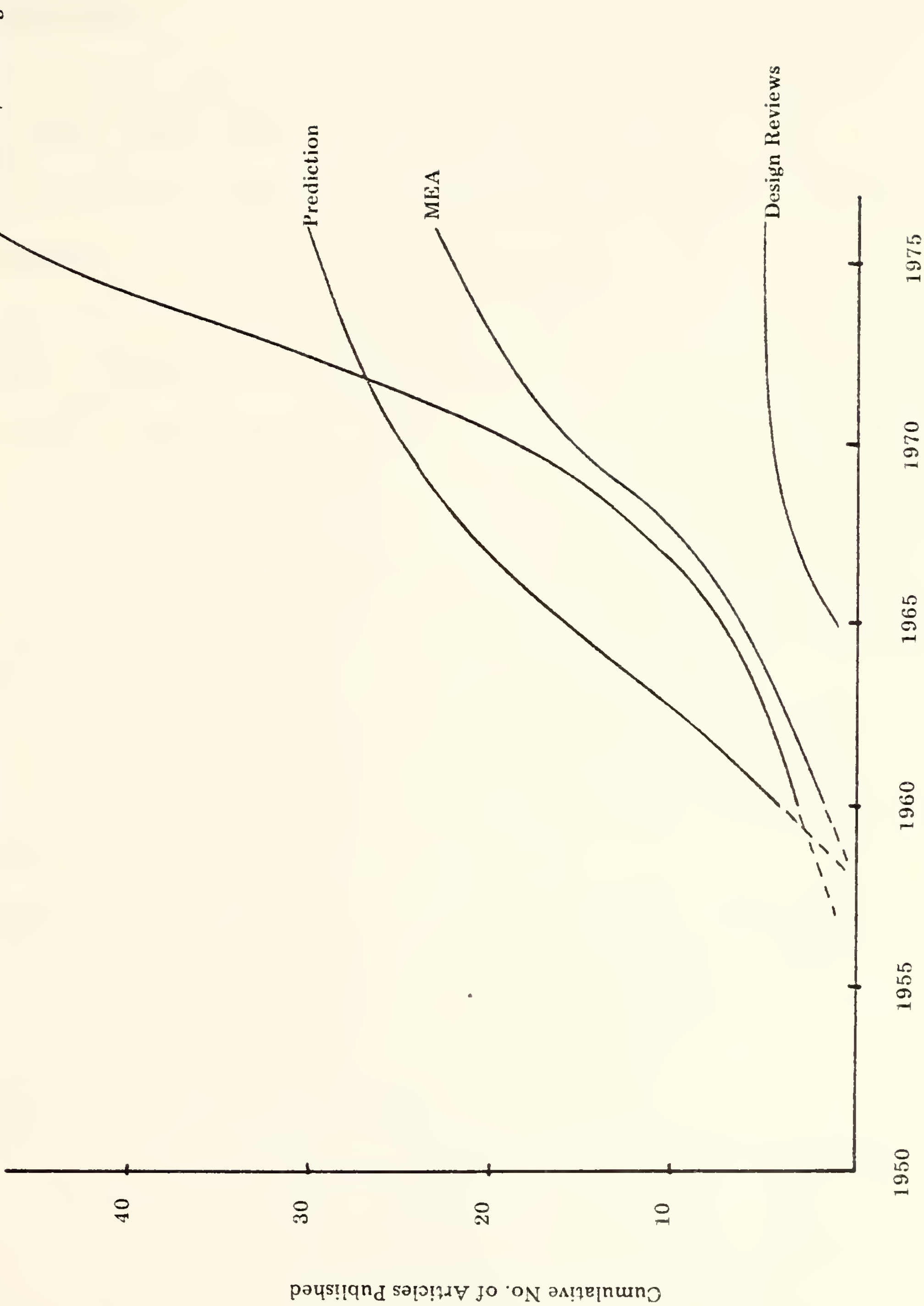
2. Analysis Branch

The literature indicates that the analysis branch can be split into Simulation/Modeling, Prediction, and Maintenance Engineering Analysis (MEA). The growth patterns exhibited in Figure 29 indicate the emphasis given the subbranches in the literature. It can be noted that prediction received a large growth stimulus in the early 1960's and then slowed down. This stimulus was primarily due to interest from the military services in developing methods of quantifying measures of maintainability. Simulation/Modeling has exhibited the largest growth in this branch as engineers attempted to develop models to test and evaluate their assumptions. This subbranch growth increased from the middle to late 1960's and then appears to have settled into a stable (and rapidly increasing) growth pattern in the 1970's. Maintenance Engineering Analysis (MEA) has also shown a strong emphasis in the 1960's with a lower, but steady growth in the 1970's. The MEA growth in the 1960's can be linked to the added interest in Integrated Logistic Support (ILS) concepts. Maintainability Design Reviews as an analytical tool seems to have received some impetus in the mid-1960's and then matured in the early 1970's.

3. Design Branch

This branch has produced several twigs and Figure 30 shows the relative emphasis each has received. Throughout the literature, human factors engineers have been described as those primarily responsible for the development of

Figure 29 M Analysis Branch



maintainability design guides. The curves indicate this interest began in the 1950's and continued through the following decade. The declining growth in the 1970's seems to reflect the maturation of ideas by the human factors engineers.

The literature shows a rising interest in qualitative attributes from 1960 through the mid-1960's. The growth leveled off in the 1970's indicating that qualitative design features had matured.

Quantitative maintainability design criteria relate to equipment features that enhance maintenance time reduction. These requirements have been specified for defense, electronic, aircraft, and missile systems for about 15 years. The rapid growth of design for quantitative requirements is graphically portrayed in Figure 30. The early quantitative maintainability specifications, established in 1960, stimulated defense contractors to put greater emphasis on design requirements. The effort to meaningfully quantify requirements continues to the present day.

Trade-off studies as a design technique sustained a high growth rate in the 1960's and then appears to have matured in the early 1970's.

4. <u>Test and Evaluation Branch</u>

The Test and Evaluation branch can be split into three main subbranches: test methods, statistics, and reporting/evaluation as shown in Figure 31. Greater emphasis appears to have been given to test methods than to either of the other two subbranches. This emphasis started in the early 1960's and has continued to the present.

Figure 30 M Design Branch

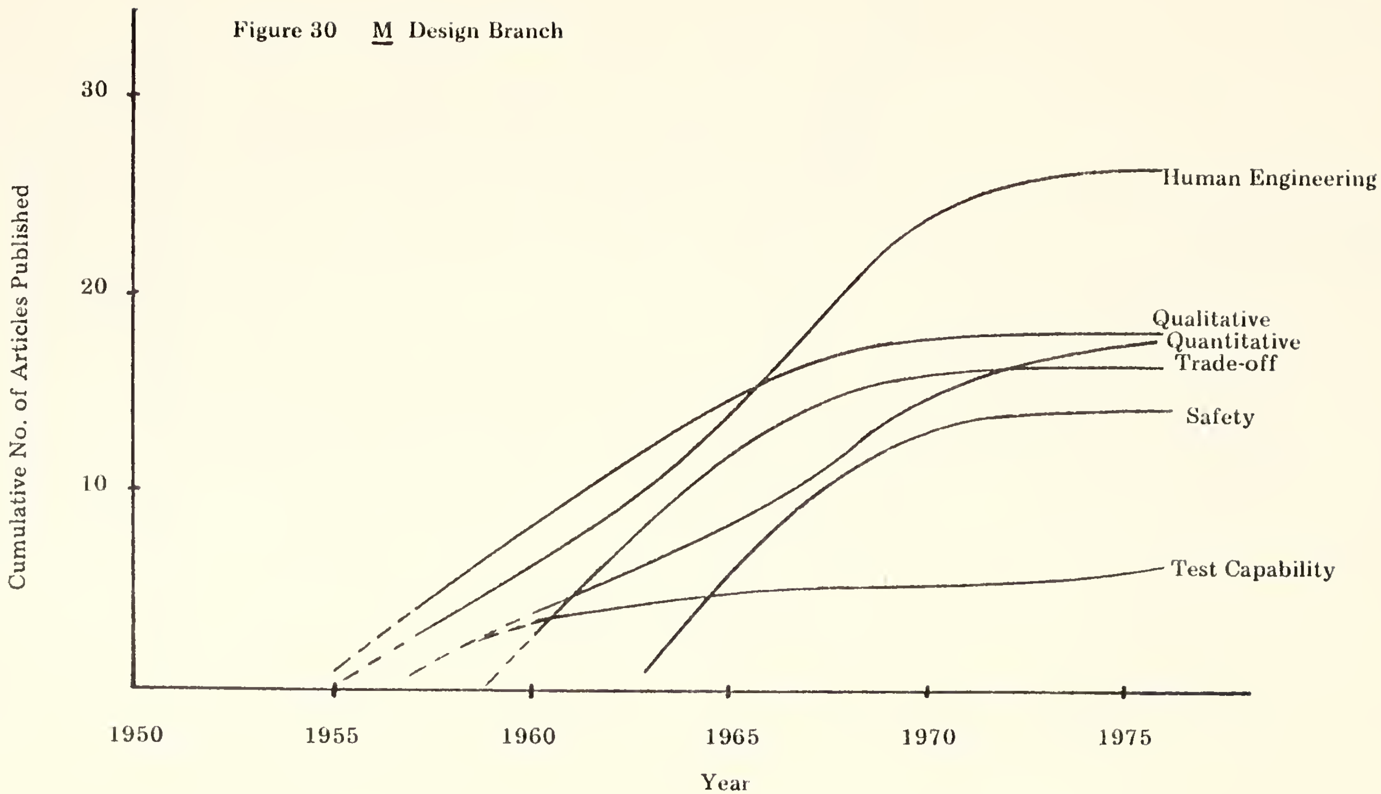
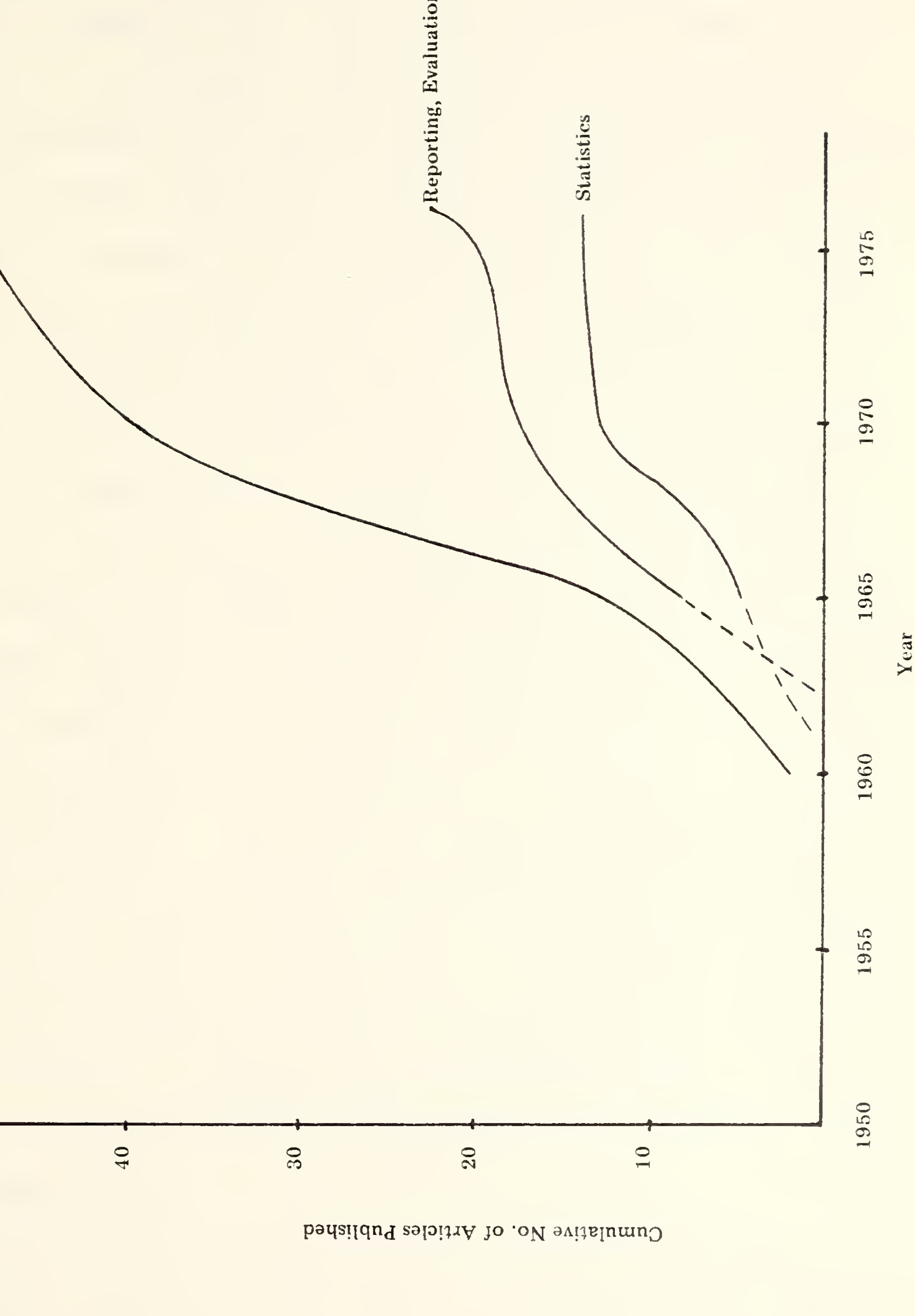


Figure 31 M Test & Evaluation



The literature clearly indicates that DOD's interest in maintainability testing started in the early 1960's. This interest has continued into the 1970's with publication of the updated Mil-Std-471A for maintainability demonstration in March, 1973. This standard established uniform procedures, test methods, and verification for evaluation of the achievement of specified maintainability requirements.

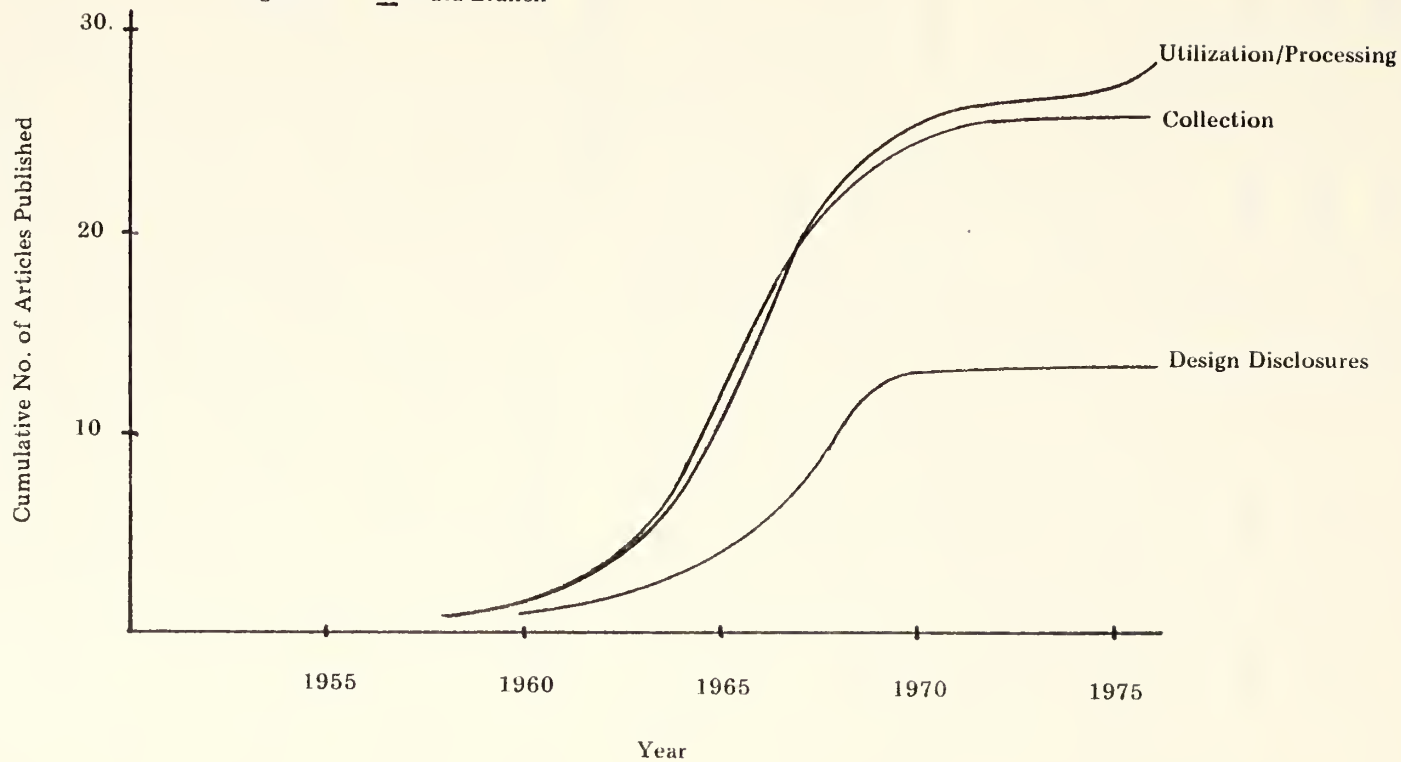
A normal carry-over from demonstration testing is the need for feedback data and other reporting mechanisms. Therefore, the reporting and evaluation subbranch received emphasis in 1965 and leveled off in the early 1970's. Additional growth has been stimulated in the mid-1970's.

The application of statistics in developing test methods has been a natural development. Maintainability demonstration, for example, is primarily concerned with the measurement of active maintenance downtime, and measurement of both preventive and corrective maintenance downtime is generally conducted as a statistical test under carefully defined conditions. Mil-Std-471A emphasizes statistical techniques in its specified test methods, test parameters (mean, median, critical percentile), assumed distributions, sample size, sample selection, and specification requirements. Interest in statistical techniques shows a steady increase starting in 1965 and maturing about 1970.

5. Data Branch

Data collection and its utilization received significant interest in the 1960's (see Figure 32). Efforts to develop maintainability data collection systems in

Figure 32 M Data Branch



response to military requirements provided a great deal of this impetus. Data collection grew dramatically in the 1960's and appears to have matured in the 1970's as the military services implemented the developed systems. The Navy 3M system is an example of such a data system. Data utilization, however, continued some growth in the 1970's and appears to be growing still. This growth can partially be attributed to the increased uses to which these data are being put; for example, quality assurance feedback, product improvement requirements, and spare parts management. The literature also indicated interest exhibited in a technique called Design Disclosure formats. This method of disclosing design information emerged in the early 1960's and appears to have matured in the 1970's.

6. <u>Management Branch</u>

This branch is the most difficult branch to assess as it has the most complex structure. In order to more clearly discuss this branch, it was decided to illustrate the structural relations as was done for reliability management (Figure 33). Figure 34 shows the five main subbranches, (1) Organization and Management, (2) Logistics, (3) Availability, (4) Procurement, and (5) Cost. Organization and Management is split into the two main twigs of Planning and Implementation and Evaluation and Assessment. The Procurement subbranch has developed two twigs, Contracts and Specifications. All subbranches showed growth patterns in the 1960 - 1970 decade. Organization and Management's growth can be traced to the military's desire to formalize

Figure 33 M Management Branch Structure

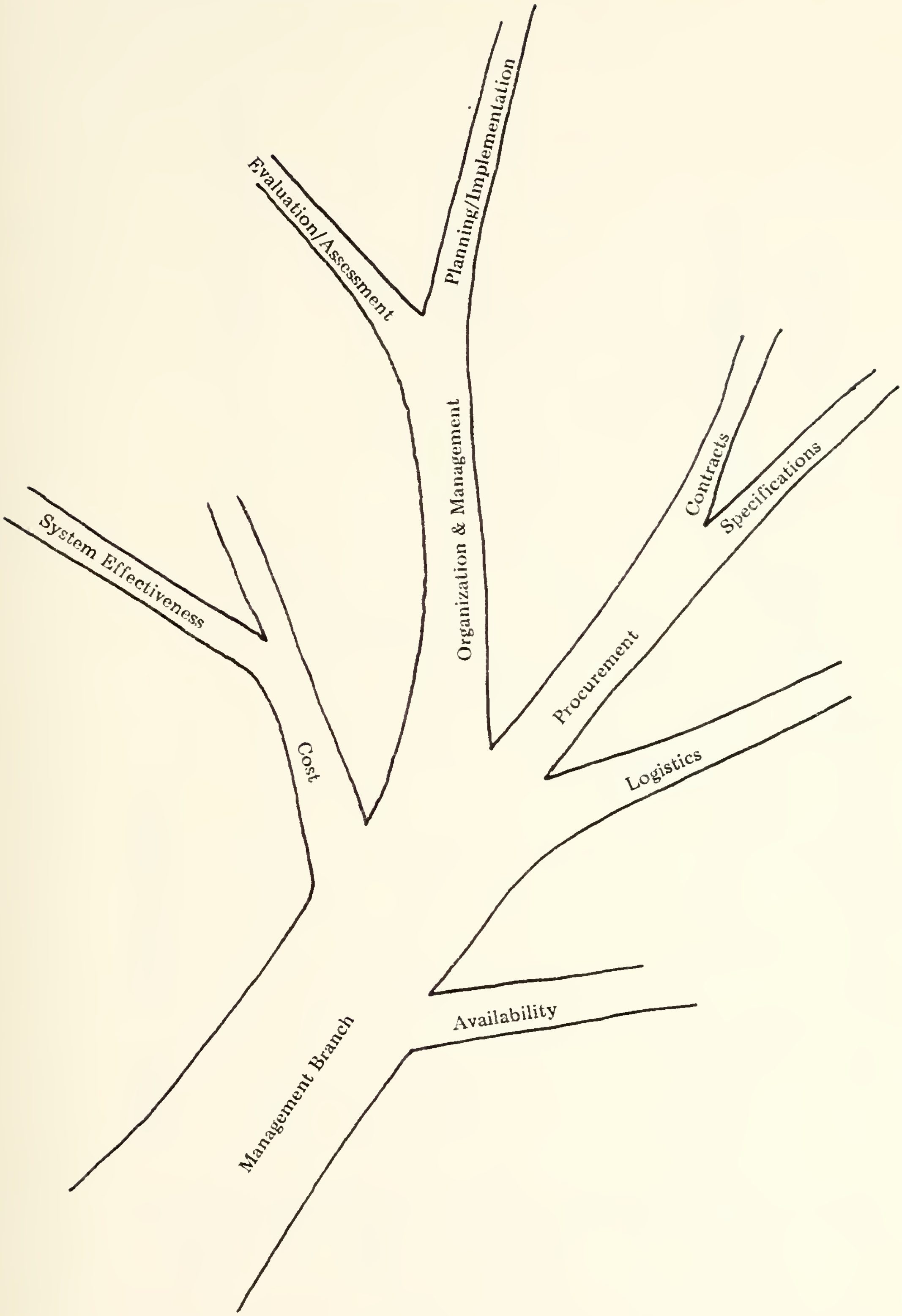
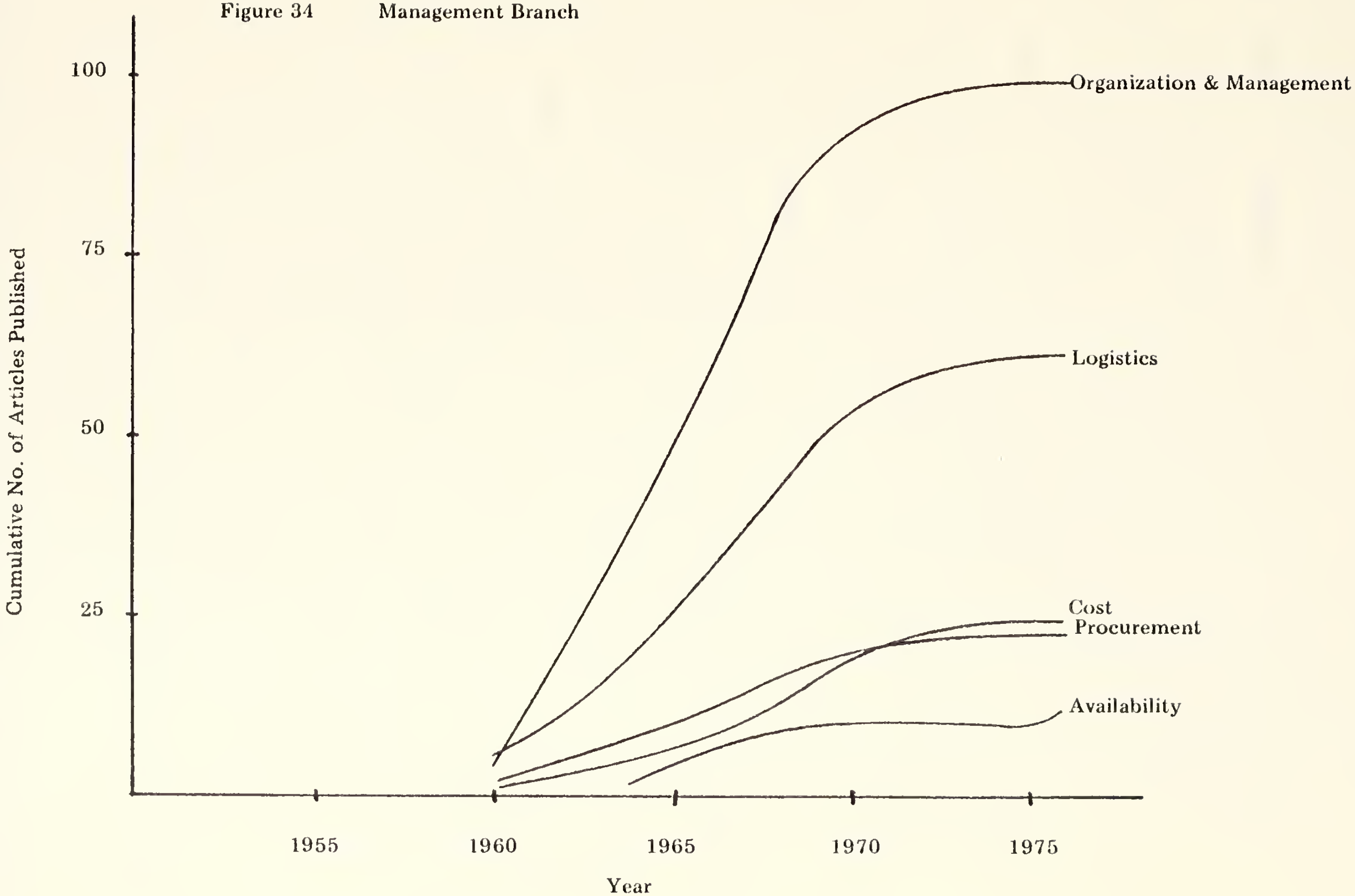


Figure 34 Management Branch

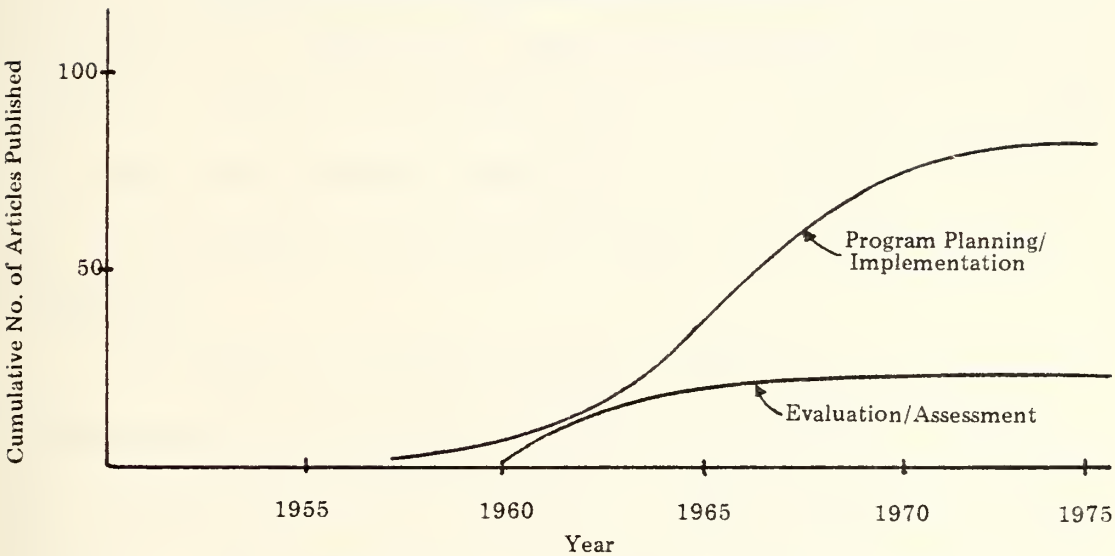


maintainability into a firm requirement. This was done when MIL-STD-470 and a number of supporting standards were issued. The curves in Figure 35 indicate that Program Planning and Implementation appeared to grow into the 1970's and shows a tendency to level off. Evaluation and Assessment techniques seemed to grow for a short period of time and then mature in the late 1960's. Logistics concerns grew dramatically in the 1960's as DOD put increased emphasis on operation and support costs. Interest in the amount of maintainability in Logistics appeared to decline in the 1970's. This indicates that usage of maintainability techniques in Logistics has matured. Availability does not show any dramatic increase other than from mid 1960's to early 1970's. This increase related to the awareness that operational Availability deals not only with failure (reliability), but also with repair (maintainability). In this time frame, many articles in the literature stressed ideas on how to improve availability by considering maintainability in addition to reliability. However, availability appears to have experienced little or no growth in the 1970's except in the past two years. Procurement's rise through the 1960's is traced to specification of maintainability requirements in military contracts. The need to specify quantitive requirements forced more consideration of maintainability in specifications.

7. Maintainability Branch Correlation with General Applications

Correlation of the most active main branches of maintainability with general applications indicates a strong

Figure 35 M Organization & Management Subbranch

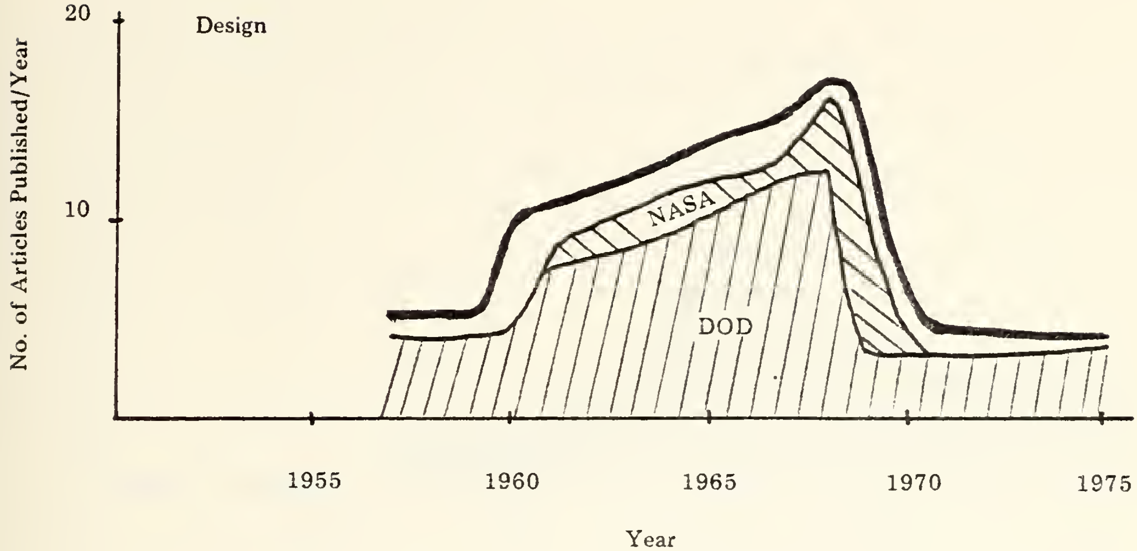


influence of maintainability interest within the Department of Defense and a lesser influence by NASA. The data base does not show a large interest in maintainability in consumables, construction, or industrial short-life equipment. The literature indicates a concern for maintainability by those companies manufacturing equipments which they sell or lease but continue to maintain throughout the equipment's service life. Computer and copying machine manufacturers are examples. The thrust for consumables was more towards reliability and quality control. Maintainability interest with respect to industrial long-life equipment appears to have been a concern in connection with commercial aircraft. Here again, the reasons appeared to be economics and customer satisfaction, since the airlines perform their own maintenance.

The heavy influence of the Department of Defense is dramatically portrayed in Figures 36 and 37. Its interest appeared in the late 1950's, rose sharply through the 1960's, then appeared to decrease just as sharply in the late 1960's and early 1970's to the levels noted in the 1950's which it has maintained through the present day.

NASA interest in maintainability has been primarily in space and its environments. The literature has been sparse with respect to number of published articles. Figures 36 and 37 show that awareness of maintainability by NASA did not really take hold until the middle 1960's and it peaked in the late 1960's when the space program design

Figure 36 Correlation of Design and Analysis with General Applications



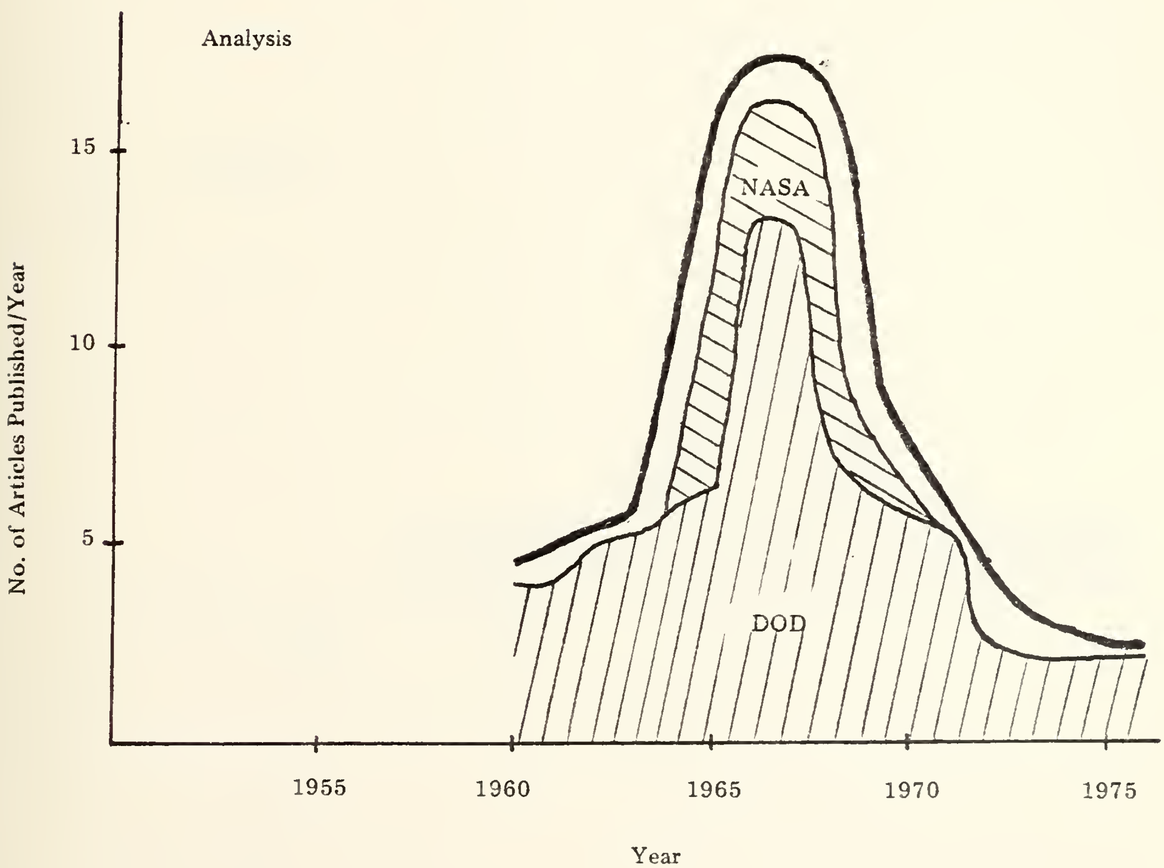
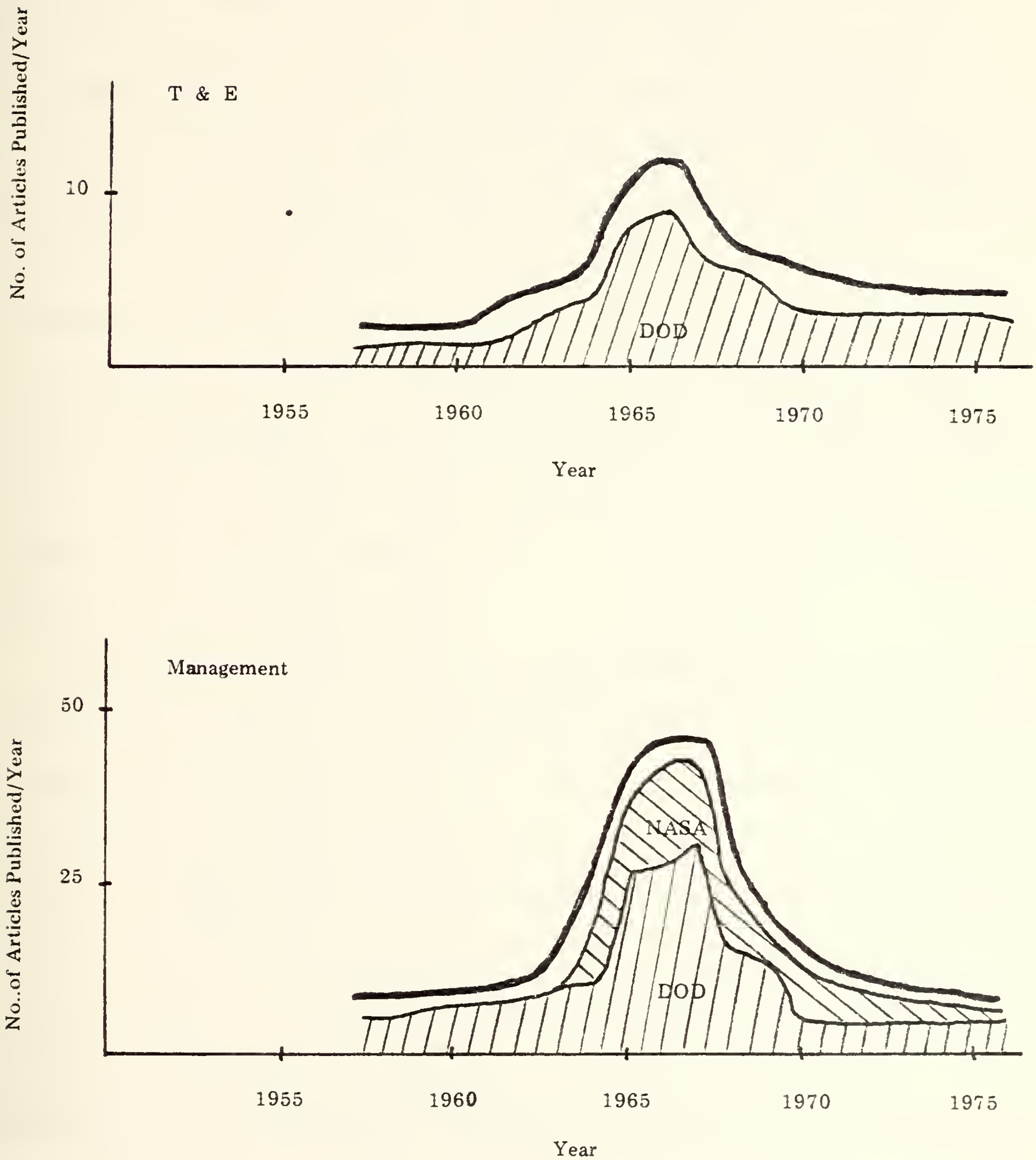


Figure 37 Correlation of T & E and Management with General Applications



was at its peak. Maintainability interest in the 1970's can be expected to increase with the skylab and space shuttle programs.

In conclusion, the greatest thrust for maintainability has come from the Department of Defense.

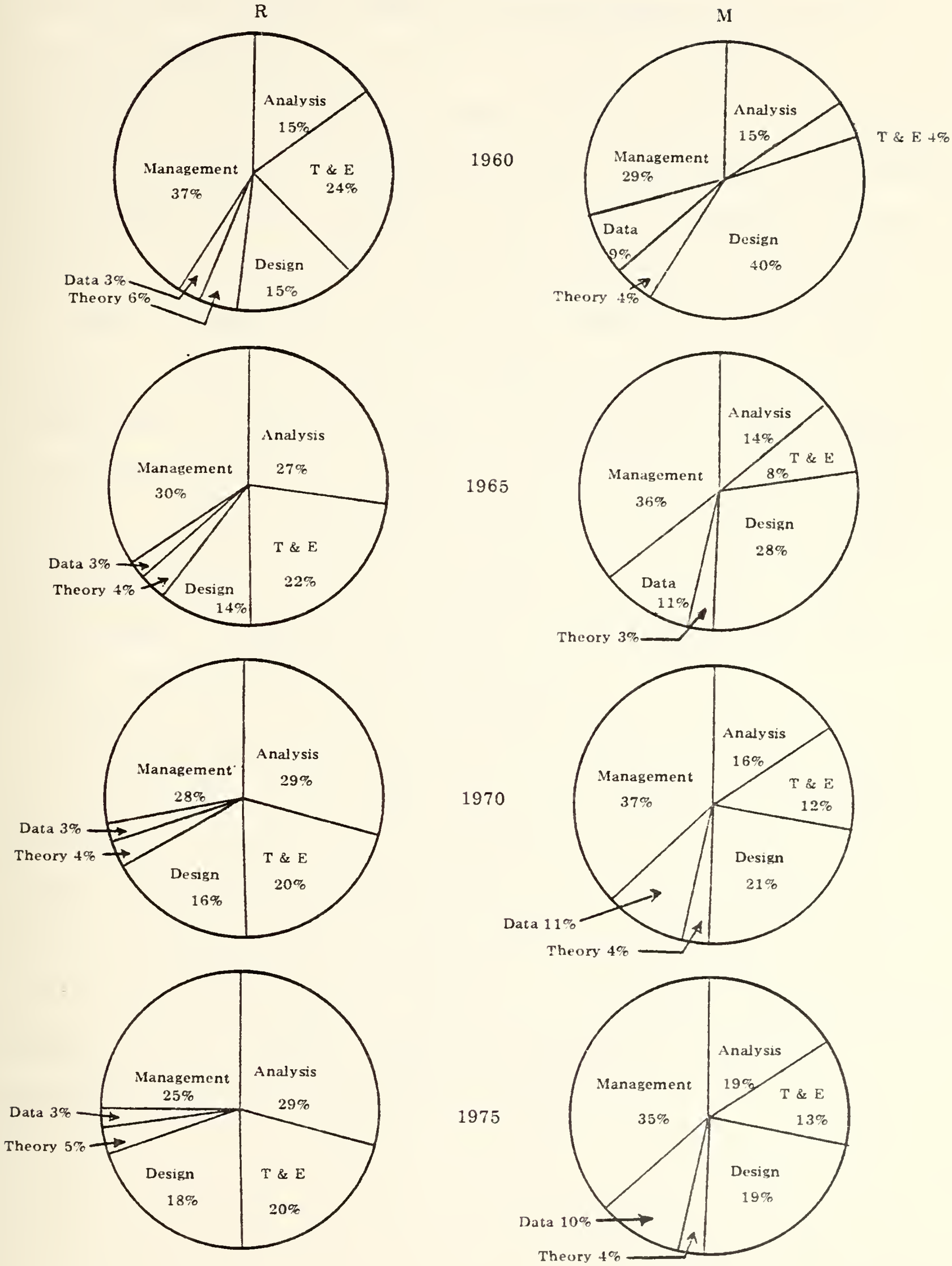
F. RELIABILITY AND MAINTAINABILITY GROWTH COMPARISON

The preceding sections in this Chapter have attempted to examine the growth of the reliability and maintainability disciplines by developing growth curves of the various branches within each discipline. The background discussions in Chapter II provided some insight into the events which affected the growth curves discussed earlier in this Chapter. Figure 38 provides an overview of the disciplines and summarizes how the emphasis has shifted within each discipline over the past fifteen years.

Figure 38 indicates that reliability and maintainability main branch growths have progressed differently in any given time period. Reliability had very high emphasis on Management and Test & Evaluation in the late 1950's and early 1960's. However, by 1965 the emphasis had started shifting more to Analysis and Design and this trend has continued to the present. Maintainability, on the other hand, had very high emphasis on design in the early 1960's, but emphasis has subsequently shifted to Management and Test & Evaluation.

These trends correlate well with the events noted in Chapter II where, for example, it was noted that some of

Figure 38 Comparison of R and M Evolutions



the concepts developed for quality control were initially applied to reliability considerations during the 1950's. Quality control has a very strong management flavor and this is reflected in the high management emphasis of reliability illustrated in Figure 38 for 1960. This area and other aspects of management have received proportionately less emphasis (with respect to the other branches) in the 1970's. The late 1950's and early 1960's saw an increase in study groups and organizations (AGREE and ARINC, for example) primarily devoted to analysis of systems and components and their influence is reflected in the dramatic increase in emphasis of Analysis (Reliability) in the mid 1960's. Design (Reliability) has also gradually received increased emphasis over the years, and this has led to development of specification and reliability design handbooks, particularly for DOD and NASA.

The initial strong Design emphasis in maintainability also produced a large number of specifications and design handbooks. However, as this discipline has grown, the flavor has shifted to Management and Test & Evaluation. Test & Evaluation (Maintainability), particularly in the form of demonstrations to satisfy procurement specifications, appears to be steadily growing in emphasis, and it is expected that this trend will continue.

V. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

Several conclusions regarding present and future emphasis of reliability and maintainability have been reached as a result of the analysis of the growth trends of the disciplines. As noted earlier, DOD and NASA have strongly influenced the development of both Reliability and Maintainability. Current trends, however, indicate that the energy (power) and the other service industries will play a major role in influencing the growth trends in the future particularly for Reliability. Maintainability growth will probably continue to be dominated by DOD because of its growing concern with the magnitude of operations and maintenance cost of weapon systems. There seems to be growing concern in DOD and the defense industry that the present specifications for reliability and maintainability required in most weapon systems contracts are outdated because of technological advances made in recent years. Reliability and Maintainability Committees of Industry Associations, such as EIA, are investigating updating these standards and specifications jointly with government agencies. Several of the maintainability branches, notably Theory, Data, and Design are approaching maturity since the literature indicates almost no activity in these areas in recent years.

Analysis is showing signs of continuing growth, although maturity may be reached in the near future. Two twigs in this

branch, Simulation/Modeling and MEA are indicating strong growth trends and it appears that this will continue.

The Management and Test and Evaluation branches also show signs of continuing growth. Two twigs in the Test and Evaluation branch, Demonstration Methods and Reporting/ Evaluation, are also exhibiting strong growth patterns at present.

Should the maintainability specifications be revised as proposed, then the Management and Test and Evaluation branches should receive renewed interest.

The emphasis within the reliability discipline in recent years has shifted from the Management and Test and Evaluation branches to the Analysis and Design branches. Nevertheless, all of the main branches of Reliability are exhibiting healthy growth patterns at present, with Analysis and Management indicating increased activity in the last two years. This increased growth rate should continue under the impetus of renewed DOD interest in Management, and especially the newly elicited interest of ERDA and the service industries in both Management and Analysis. Applications of the techniques developed in the Analysis and Design branches to computational and power generation problems appear to be fast growing areas at present. This is particularly true of Power Generation which has established a phenomenal growth rate in the last three years and progress in this area should be very interesting to monitor in the future. Several twigs have emerged which show promise of high continued growth in the future. These twigs, in conjunction with their motivational impetus are listed below

TWIG	MOTIVATION
1. System Effectiveness (cost)	DOD and Service
2. Prediction	DOD and Service
3. Modeling/Simulation	DOD and Service
4. Warranties & Specifications	DOD and Service; Consumer/Legal
5. Product Liability	Consumer/Legal

The twig, Product Liability, is potentially a very complex area with safety and reliability issues combined with the complicated legal implications involved with consumer protection. This twig is experiencing a substantial growth rate. These issues are important because court decisions could have significant effects on the amount of Analysis and Testing a manufacturer may have to undertake in order to demonstrate that his product is reliable and to precisely define the environmental rating.

It appears that the literature in recent years has been devoting progressively more attention to the implications of equipment reliability on safety issues. Analysis techniques such as Fault Trees have been developed which are useful in both reliability and safety analysis. Many articles have dealt with these techniques as utilized in safety analysis as well as the effect of "unreliability" on safety. This area has been noticeably growing in the recent past and appears to have potential for rapid development in the immediate future.

B. RECOMMENDATIONS FOR FUTURE EFFORT

1. Continue to update the data base with latest symposia proceedings. This effort has produced an extensive data base for the reliability and maintainability disciplines classified by keywords along the dimensions discussed in Chapter III. This data base, if kept current, represents a valuable source of information which is easily retrievable for research purposes.

2. Publish a bibliography on reliability and maintainability. The data base on reliability and maintainability should be made available to other persons working in the disciplines.

3. Develop the evolution of safety over the decades. The safety discipline is closely interrelated with reliability and maintainability and if developed would be a valuable source of information to future researchers.

4. Present the taxonomies to symposia and professional societies for acceptance as standard classification systems. The taxonomies are composed of hierarchical ordered keywords whose structural relationships have been documented. The structural relationships are considered to be superior to those presently in existence.

5. Expand the data base to include technical reports and classified documents. This will tend to fill in voids left by the current data base and provide a more complete analysis of the trends established herein.

APPENDIX A

TAXONOMY KEYWORD GLOSSARY

A.0. INTRODUCTION

This glossary of taxonomy keywords is presented to provide the reader with the keyword definitions used by the authors to insure consistency in article keyword assignment. The glossary addresses only those taxonomy keywords about which there was some definition disagreement amongst the authors, or which was required for reader clarification. The glossary is not intended to be a dictionary of reliability and maintainability terms for general use.

The keyword definitions, where possible, have been taken from the literature when it appeared that the definition had general usage. Definitions were generated for keywords that did not have generally accepted definitions and these definitions have been identified by asterisks. Keywords which have generally accepted definitions such as Mechanical or Communications, and keywords which are taxonomy headings, such as Management and Prediction, have not been defined. Where needed for clarity, the taxonomy branch to which the keyword being defined belongs has been parenthetically inserted following the keyword.

A.1. DEFINITIONS

AEC/ERDA - articles which deal with energy either sponsored by or written for the Atomic Energy Commission or the Energy Resource Development Agency.

*Analysis and Evaluation - (Test & Evaluation) process of working with the reported test results to arrive at conclusions relative to the item tested.

Apportionment - an allocation of the overall numerical reliability or maintainability requirements among each of the elements of a system.

Attribute/Parameter Estimation - (Test & Evaluation) - measurement and/or correlation of some characteristic of a part or system by test procedures wherein the characteristic is quantitatively or qualitatively estimated by analyzing the test data to determine if the part/system possesses the characteristic.

Availability - the probability that the system is operating satisfactorily or is ready to be placed in operation at any point in time under stated conditions of use.

*Bayesian - technique of modifying conclusions reached about present data based on historical knowledge of the data characteristics.

*Block Diagram - a graphical method relating system success to component successes.

Burn-in - the operation of an item, component or system to stabilize its characteristics or to weed out its faults prior to placing the item in use.

*Case Studies - how specific reliability or maintainability programs were approached and/or how specific program problems were resolved. The essence of these articles is not analytical but rather lessons learned for discussions of "How we did what."

*Component Testing (Design) - subjecting components or systems to environments designed to verify that they will perform their intended function in the environments in which they will be utilized.

*Consumables - items such as ammunition, food and fuel which are expended during operation of the system.

*Consumer Capital Item - items such as automobiles and appliances, which by virtue of their cost and life duration represent a significant portion of the average citizen's budget.

*Cost - the costs, monetary or otherwise, of a reliability or maintainability program, including articles concerning major programs or concepts, such as design-to-cost, operation and maintenance costs, and their relationship to reliability and maintainability.

*Criteria/Requirements (Design) - goals and specified performance values which components and/or systems are expected to achieve in their operational environment.

Criticality Analysis - a quantitative method of ranking the failure modes according to the criticality of their effects to their probability of occurrence.

*Data Collection - methods, forms, practices, etc., for the acquisition and storage of data concerning the performance of specified entities.

*Data Exchange - programs for the exchange of data within the reliability and maintainability communities. The definition includes articles presenting bibliographies developed to facilitate the exchange.

*Data Utilization - purposes for which information concerning systems or component performance is to be collected.

Design Disclosure Format (Data) - a method of presenting critical maintainability data for the system under design in a manner that facilitates analysis.

*Design of Experiments (Test & Evaluation) - development of test procedures/methods in such a way that statistical principles may be utilized in working with the test data and in reaching conclusions.

*Design Reviews (Analysis) - a comprehensive critical audit of all aspects of the design of the hardware and software.

*Design Reviews (Management) - management reviews of reliability and maintainability programs. These reviews tend to be macro program reviews vice the more micro design reviews identified under analysis.

*DOD - articles dealing with defense applications sponsored by or written for or about the Department of Defense.

*Failure Recurrence Control - articles concerning management efforts to curtail and/or preclude the recurrence of reliability failures. Includes articles addressing reliability failures which arise during or as a result of development or production.

Fault Tree - a graphical method using logic calculus to relate system failures to component failures or failure modes.

*Field Activity - end user conditions caused by inadequate reliability or maintainability, and efforts to improve or rectify the situation.

FMEA - a qualitative technique for analyzing and evaluating a design by singling out failure modes and analyzing the consequences and causes.

*General (Functional Area) - articles which do not address a functional area, or articles where the functional area though addressed is immaterial to the essence of the article.

*Goodness of Fit - technique to determine if a group of data can be expected to behave in accordance with a hypothesized probability distribution at some predetermined level of significance.

*Government (Other) - articles dealing with applications sponsored by government agencies other than AEC/ERDA, NASA, or DOD. This includes foreign governments.

*High Reliability Parts (Design) - those parts or components which by virtue of design, construction or testing are more resistant to failure than parts with similar form, fit and function.

Human Engineering - the area of human factors which applies scientific knowledge to the design of items to achieve effective man-machine integration and utilization.

*Industrial Long Life or High Cost - items such as heavy machine tools which require a significant portion of an industrial concern's capital budget.

*Industrial Short Life or Low Cost - items, such as test equipment, utilized for industrial purposes which represent expensed rather than capitalized expenditures or which represent a small portion of an industrial concern's budget.

Logistics - the procurement, movement, maintenance and disposition of supplies, equipment, facilities and personnel, and the provision of services.

MEA - the formal process of reviewing a design or proposed design for the purpose of identifying and quantifying the maintenance and support requirements for an operational system.

Measure - the use of theory which allows quantification of maintainability parameters so they can be measured.

Modeling - conceptualizing the interactions of the elements comprising an entity in quantifiable terms usually for the purposes of behavior prediction and/or forming hypotheses about current or past behavior.

*<u>NASA</u> - articles which deal with space applications sponsored by or written for or about the National Aeronautics and Space Administration.

*<u>Non-reversible</u> - devices which depend upon some physical, chemical or biological reaction or effect which once started cannot be reversed or changed back to its original form or state.

*<u>Parameter Prediction</u> - techniques for estimating the characteristics of a population based on the knowledge of the behavior of a sample drawn from the population or a knowledge of its constituent parts, functions and operating environment.

*<u>Part/Material Selection</u> - selection of those parts which, by design or from test results, are more failure resistant than similar parts.

<u>Probability Distribution</u> - a mathematical description of the relative frequency with which the various outcomes of an experiment can be expected to occur.

*<u>Product Liability</u> - implied responsibility of manufacturer to ensure that their products perform their mission safely and satisfactorily. Consequences of product failures may be found to be responsibility of product manufacturer.

*<u>Program Evaluation</u> (Management) - assessment and interpretation of reliability or maintainability programs.

*<u>Qualitative Attributes</u> - those techniques such as accessibility, test points, that allow ease of maintenance.

*<u>Quantitative Attributes</u> - those characteristics that can be assessed and measured or demonstrated during established design, development, production, and field use milestones.

<u>Redundancy</u> (Reliability, Design) - the existence of more than one path for accomplishing a given task, where all means must fail before there is an over-all failure of the system.

*<u>Reliability Growth</u> - the process of predicting future reliability achievements by extrapolating measured data on current reliability characteristics.

<u>Renewal Theory</u> - the study of certain probability problems which can arise in connection with the failure and replacement of components.

<u>Safety Factor</u> - the margin of conservativeness inherent in the application of component parts as a function of all stresses. Includes using components in environments less stressful then normally designed for (derating).

Sampling/Screening Plan - a statement of the sample size or sizes to be used and the associated acceptance and rejection criteria.

*Service - articles sponsored by or written for or about the service industries, (ie. utilities, airlines, telephone).

*Simulation/Modeling - conceptualizing the interactions of the elements comprising an entity in quantifiable terms, usually for the purposes of behavior prediction and/or forming hypotheses about current or past behavior.

Specifications (Procurement) - considerations related to specifications or the statement of work.

System Effectiveness (Cost) - the measure of the extent to which a system can be expected to complete its assigned mission within an established time frame under stated environmental conditions.

*Test Equipment - equipment utilized to subject components or systems to conditions designed to verify the item's performance under specified conditions.

*Testing/Demonstration Methods - techniques to measure whether systems, components, etc., will perform at specified or required levels.

Tolerance Analysis - study of the allowable variation in values of a component or system characteristics within which the characteristics are judged acceptable.

Trade-off - a process of optimization of the related factors involved during the life cycle of an equipment or system to determine an optimal balance among these factors to accomplish a specified objective.

*Unspecified (Application, General) - application unspecified in the article.

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